A REVIEW OF THE INDUSTRIAL DEVELOPMENT AND USAGE OF ELECTRONIC GOVERNORS

by

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ABSTRACT

The paper presents a review of electronic governors as developed and used by industry. The current interest in the conservation of energy has led many users of prime mover equipment to develop better control technology for their equipment. This paper deals with the development of the electronic governor and discusses the effects of these control devices on the operation of the industrial equipment.

The basic operation of governors is discussed, with the fundamental operational behavior of governors being presented, including a brief review of the applicable control theory parameters. Also, the industrial development and usage of the electronic governor is described. Several areas are pointed out by industrial users for development of electronic governors. The operational characteristics of several electronic governors are given along with the advantages and disadvantages of using these governors.

INTRODUCTION

Sooner or later, everyone concerned with power generating equipment becomes involved with controls, either from the technical or economic standpoint. Perhaps no other aspect of turbine application and specification receives as much attention as does the type and quality of speed governing apparatus. The wide variety of available control (or governing) systems, in all degrees of simplicity or sophistication, permits the selection of a governor ideally matched to the characteristics of the driven machine and the load profiles.

Industry, with its emphasis on energy conservation and system efficiency, has started to develop the technology for better control and operation of its prime mover equipment. The development of the control aspects has resulted not only from the need for better efficiency, but primarily from the fact that existing controls were not sufficient enough to provide the necessary operating service required.

In order to provide some background to assist in the understanding of the operation and usage of electronic governors, the paper will begin with the fundamentals of control systems and then progress to the industrial application of governors. In the following sections, a review of the basic control concepts utilized on turbines will be made; then the experiences gained from industrial usage of those concepts will be reviewed. From these experiences the advent of the industrial usage of electronic governors will be detailed, and a review of the operation of typical electronic governor systems will be given.

CONTROLS

Unfortunately, controls are complicated mechanisms, and the theory of their operation cannot be completely understood without a knowledge of advanced mathematics. Nevertheless, it is the intention of the author that the material in the first part of this paper will provide some practical insight into control theory and governors, as well as a degree of familiarity with the available hardware, for those whose primary responsibility is other than control engineering.

The control of speed is obviously required when a turbine drives an alternator, and most other industrial applications also require speed control for one reason or another. Even in aircraft turbojet engines, where speed in itself is not important for any functional reason, the relatively narrow limits imposed on rotative speed (and turbine temperature) by engine performance requirements on the one hand and engine stresses on the other make some form of speed control mandatory.

The speed governor's job is really two-fold: first, it must provide stable control of system speed, that is, keep the desired speed at a substantially constant value with no variations above or below this value; secondly, it must return the speed to this value following a change in load on the machine, with a minimum of overshooting and in as short a time as possible. The governor configuration giving the best steady state control does not necessarily give the best performance on load transients. Usually, the better the job the governor is required to do, the more expensive it becomes. These technical and economic trade-offs must be considered for each application.

Another control, operating to protect the engine against over or under fueling, is generally required. It works in conjunction with the speed governor and prevents the latter from making such large and rapid changes in fuel flow that would result in stall or excessive temperatures on the one hand and unstable combustion or lean blowout on the other. This control is generally either a scheduling device, computing the maximum and minimum fuel limits for each operating condition from one or more devices sensing various parameters of this condition, or else a device which measures turbine temperature directly.

Finally, additional controls may be required to position stator vanes, to operate compressor bleeds, regenerator bypasses, etc., or to keep engine pressures and temperatures within the normal running limits. Other controls, to safeguard the turbine from excessive temperatures and speeds resulting from malfunction of the primary control system, and to sequence starting, loading, unloading, and stopping the machine, may also be required.

Control Elements

Consider first the control characteristics of a simple prime mover and a somewhat oversimplified servo type speed governor. In this connection, "control characteristics" means the behavior of the prime mover and its governor while the speed is changing. Most people concerned with prime movers are interested in such "steady state" characteristics as specific fuel consumption and maximum continuous power ratings. Control people, on the other hand, are principally interested in such dynamic phenomena as what happens to the speed of the prime mover when the load is changed.

Both the prime mover and its governor may be considered as devices having an input and an output, the input being a variable which determines the value of the output. The input to the prime mover is the fuel valve controlled position and the output is speed, if that is what we are controlling. Speed is, of course, the input to the governor, and its output is fuel valve position. When the prime mover and its governor are connected together, output to input, we have a "closed control loop," as seen in Figure 1.

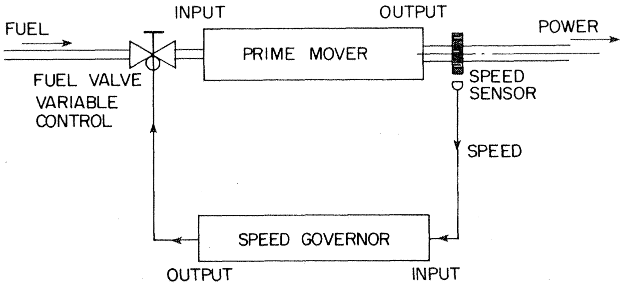

Figure 1. Closed Control Loop [1].

To assist in the understanding of the techniques used in the control of prime movers, the following sections will describe various aspects of the governor.

GOVERNORS

The Basic Governor

For an illustration of the basic governor, assume a device as shown in Figure 2. It consists of a speed weighing element on the left and a power operated throttle actuator on the right. The L-shaped flyweights, pivotally mounted on a ballhead which is driven by the turbine, convert the rotative speed to an upward force on the thrust bearing. A balancing downward force is established by the speed reference spring. When the speed is at the desired value, the flyweights will be in the vertical position as shown. A decrease in speed will allow the spring to force the thrust bearing downward, while an increase in speed will cause the flyweights to lift the bearing.

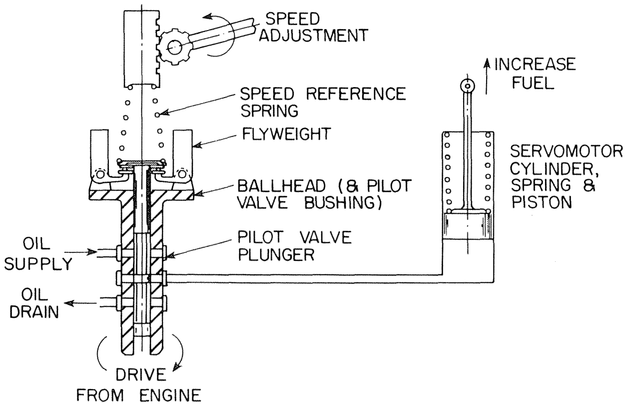

Figure 2. Example Governor.

Attached to the upper race of the bearing is a spool-type hydraulic valve plunger, which operates with holes drilled in the rotating bushing to let high pressure oil into the servomotor when the valve plunger is below center, and allows it to drain out of the servomotor, under the urging of the heavy spring in the rod end of the servo, when the plunger is above center. When the plunger is centered as shown, the oil is trapped in the head end of the servo, and the piston cannot move.

When this governor is mounted on a prime mover and the ballhead is driven by it, the servomotor piston will not move as long as the speed remains at the value for which the reference spring is set. If the speed falls below the desired value, pressurized oil will be admitted under the servo piston and will force it in the direction to increase fuel. If the speed goes above the set value, the flyweights will lift the valve plunger and connect the head end of the servo cylinder to the drain, and the spring will move the servo piston down to reduce fuel flow.

The previous description outlined the fundamental operation of the basic governor. The operation of other types of governors and the performance characteristics of these governors will now be discussed.

The Speed Governor

The steam turbine governing system consists of the following basic parts: (1) a speed governor (mechanical, hydraulic, electrical); (2) a speed-control mechanism (relays, servomotors, pressure or power amplifying devices, levers and linkages); (3) governor-controlled valve or valves; (4) a speed changer; and (5) external control devices, as required.

The control of steam turbines is achieved by manipulating the steam inlet valve. Therefore, in order to control turbine speed, a mechanism must be provided which opens the inlet steam valve or rack if the steam turbine slows down and closes the inlet valve or rack if the steam turbine speeds up.

An increase in load will slow a turbine, and a decrease in load will cause a turbine to speed up. Since a change in load causes a change in speed, a speed control device can also be a load controller.

Although control of gas turbines can be more complex, the speed control of steam turbines and gas turbines is basically the same. Some mechanism must measure the speed of rotation. A function then must compare this speed measurement to a desired setting, called a set point. Whenever a deviation occurs in the form of a speed or load change, the governor (or speed controller) must then act on the turbine to return the speed measurement toward the set point. This control action may be achieved in a number of ways.

There are pure mechanical governors and hydraulic governors; and a combination of these two, a mechanical/hydraulic governor, is also used [2]. There are electronic governors, and there are electro/hydraulic governors. Each has advantages. In each case, however, the governor must measure the speed of rotation or rpm. Each, however, must be capable of opening the steam valve as the turbine slows and closing the valve as the turbine accelerates. In a gas turbine the governor opens and closes the fuel control valve, rather than the steam inlet valve. There are various restraints in each case, but the basic function of a governor, or speed controller, remains the same.

A governor cannot control at a fixed speed. As an example, let's say a turbine is set to operate at 3,000 rpm with a "fixed speed" controller. If the turbine slowed to 2,999 rpm, the steam inlet valve would open fully and the turbine might increase in speed to 3,001 rpm. Then, the valve would close and the speed might fall back to 2,999 rpm. Such action is called "on-off control" and will cause turbine speed to constantly oscillate. To prevent this instability, governors are set to operate within a speed range. For instance, the steam valve might normally be half open at 3,000 rpm, fully closed at 3,010 rpm, and fully open at 2,990 rpm. The set speed is then 3,000 rpm with a speed range of plus or minus 10 rpm. Rotating equipment people normally refer to this action as "droop." People in instrumentation or controls would call this action "proportional action," or more recently, "gain."

One simple type of mechanical governor is a fly-ball governor as shown in Figure 3. This governor consists of a set of weights, or fly-balls, connected to the shaft and held together by a spring. As the shaft spins, centrifugal force moves the fly-balls apart. If the shaft spins faster, the fly-balls move further apart, and if the shaft spins slower, the fly-balls move closer together. The spinning fly-balls are connected to the steam inlet valve by a linkage. When the shaft spins faster, the fly-balls move further apart, causing the linkage to move. This linkage movement will serve to close the valve, and therefore, the turbine speed will remain within the control range. When the turbine shaft spins slower, the fly-balls will move closer together, causing the linkage to move in the opposite direction. Now the linkage movement will serve to open the valve, thus keeping the turbine within the speed control range. Remember, if the turbine slows down, the governor opens the steam valve and if the turbine speeds up, the governor closes the steam valve. This action is known as "feedback." Information about the output of the machine (rotation) is fed to the governor, which influences the speed of the machine (steam admitted), which in turn, influences the output again (rotation). Note that the feedback is negative, that is, increasing speed produces action tending to decrease speed; likewise, decreasing speed produces action tending to increase speed.

Fly-ball governors work best when shaft speed is relatively low, on the order of 1,000 to 2,000 rpm or less. Some 3,600 rpm steam turbines have been equipped with direct drive fly-ball governors. At these higher rotational speeds, however, the mechanism is frequently prone to fail. Steam turbines operating at higher speeds are normally provided with a gear reduction assembly, so that a turbine running at 6,000 to 12,000 rpm may drive a reduction gear to provide speeds of less than 1,000 rpm for the fly-ball mechanism. The wear, lubrication, and maintenance problems are all magnified in this type of installation and it is frequently an unsatisfactory application for speed control.

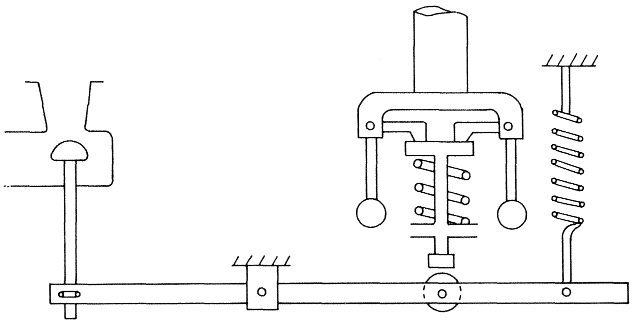

Figure 3. Direct-Acting Flyball-Type Governor.

The centrifugal force exerted by the spinning weights in a fly-ball governor is limited. Even if very large weights are used, only a limited force is available to move the inlet steam valve. Steam pressure at the inlet valve produces a force opposing the fly-ball action, and steam deposits on the valve parts cause the valve to stick. Sometimes the limited force of the direct acting fly-ball governor cannot overcome this opposing force and sticking. There are other drawbacks to the fly-ball governor. Mechanical wear of the components results in lower accuracy of control response and, sometimes, governor failure. A certain level of maintenance is necessary to keep this governor in good working order. To perform this maintenance, the machine must be shut down.

The speed governor, a basic part of the turbine, should be directly responsive to turbine speed and should initiate action of the other parts of the governing system. The simplest form of speed governor is the direct acting fly-ball type described above. Capable of adjusting speeds through about a 20% range, it finds use on single-stage mechanical-drive steam turbines with speeds up to 5,000 RPM and steam pressures up to 600 psig.

NEMA classifies steam-turbine governors as shown in Table 1 [3].

Operating Modes

In the controlled system we are concerned with three types of governor operation: isochronous, speed droop and load limit (which is a high throttle limit operation when in control). These are represented, as suggested, as plots of engine load (assumed proportional to servo or rack position) versus speed [4].

1. The isochronous governor performance may be represented by a family of horizontal lines, each line representing a speed setting. If set to maintain the speed represented by line A in Figure 4, and connected to an increasing nonsynchronous load, the speed would vary as follows. Beginning with no load, the speed will remain constant at A as load is increased until the capacity of the engine is reached, and then as load is further increased, speed will drop, the rack remaining at its maximum position.

2. The speed droop governor has a similar family of curves, but slanted as shown; the greater the regulation, the greater the slope (Figure 5).

TABLE 1. NEMA CLASSIFICATION OF SPEED GOVERNORS.

Class of Governor	Adjustable Speed Range, %	Maximum Steady State Speed Regulation, %	Maximum Speed Variation, % Plus or Minus	Maximum Speed Rise, %	Trip Speed, % (Above Rated Speed)
A	10-65	10	0.75	13	15
B	10-80	6	0.50	7	10
C	10-80	4	0.25	7	10
D	10-90	0.50	0.25	7	10

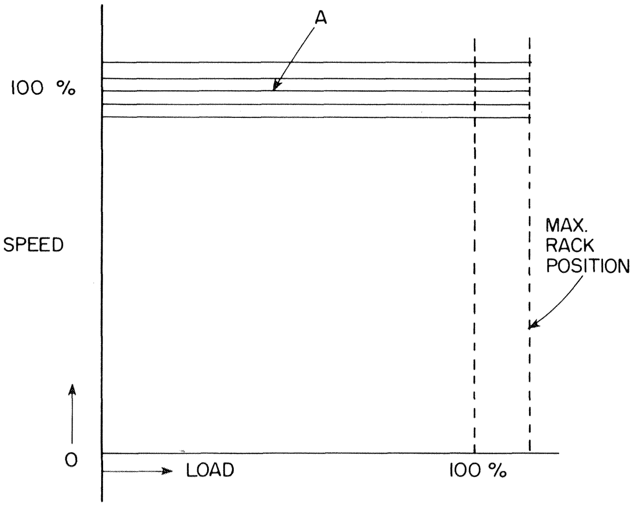

Figure 4. Isochronous Governor Performance.

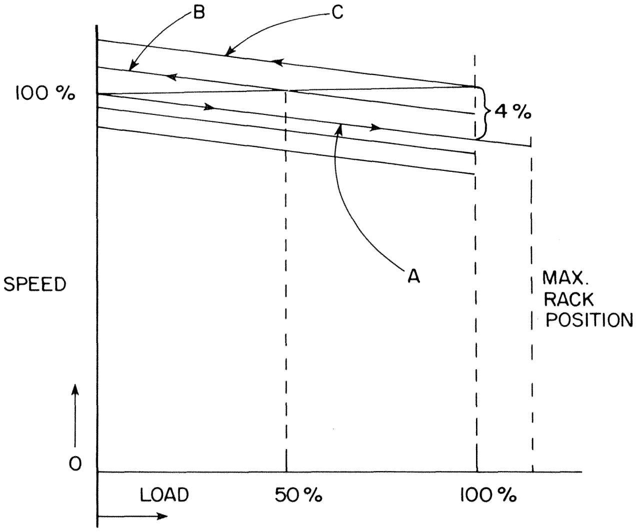

Figure 5. Speed Droop Governor Performance.

3. Similarly loaded, the speed will drop down the regulation line until maximum rack is reached and continue to drop at maximum rack as load is further increased. Suppose now that the load limit is set at 50% in either case (Figure 5). The behavior is the same as before except that now the speed drops from the setting line when load limit torque (50%) is reached instead of when the normal rack limit is encountered. Assume the speed droop governed machine is connected to a synchronous system so large that our engine cannot affect its frequency. Now we must remember that the speed of the engine is no longer determined by the speed setting, but by the frequency of the turbine so long as maximum synchronizing torque is not exceeded. What is accomplished by a change in speed setting in this case is a change in load, not in speed. Referring again to Figure 5, we must have setting A for which the no load speed is equal to turbine speed (or frequency) in order to synchronize the system. Once on the line, if we increase speed setting to B, we do not change speed but we pick up approximately one-half load. Further increase in setting to line C will fully load the engine. If regulation, as indicated by slope of lines, is 4% and the load is disconnected from the turbine while carrying one-half load, the free engine will go up in steady-state speed 2%. If set on line C, carrying full load and similarly disconnected, the no load speed would be 4% above synchronous or 100% speed. If the speed droop were zero, that is, if the governor were isochronous, paralleling with an infinite load would be impractical for the reason that a speed setting above synchronous speed by however small an amount would call for full rack, since actual speed would be below the setting. Similarly if the setting were even slightly below actual speed, the racks would go to fuel off position. Therefore, governors should not be paralleled isochronously.

Operating Definitions

The following definitions are given in order to provide a better understanding of the operating terminology used with governors, as given by the NEMA classifications.

1. *Range of speed-changer adjustment*, expressed as a percentage of rated speed, is the range through which the turbine speed may be adjusted downward from rated speed by the speed-changer, with the turbine operating under the control of the speed governor and passing a steam flow equal to the flow at rated power output and speed.

The range of the speed-changer adjustment, expressed as a percentage of rated speed, is derived from the following equation:

$$\text{Percent} = \frac{\begin{pmatrix}\text{Rated}\\ \text{Speed}\end{pmatrix} - \begin{pmatrix}\text{Minimum speed}\\ \text{setting}\end{pmatrix}}{\text{Rated Speed}} \times 100$$

2. *Steady-state speed regulation*, expressed as a percentage of rated speed, is the change in sustained speed when the power output of the turbine is gradually changed from rated power output to zero power output under the following conditions:

a. The steam conditions (initial pressure, initial temperature, and exhaust pressure) are set at rated values and held constant.

b. The speed-changer is adjusted to give rated speed with rated power output.

c. Any external control device is rendered inoperative and blocked in the open position so as to offer no restrictions to the free flow of steam to the governor-controlled valve(s).

The steady-state speed regulation, expressed as a percentage of rated speed, is derived from the following equation:

$$\text{Percent} = \frac{\begin{pmatrix}\text{Speed at zero}\\ \text{power output}\end{pmatrix} - \begin{pmatrix}\text{Speed at rated}\\ \text{power output}\end{pmatrix}}{\text{Speed at rated power output}} \times 100$$

Steady state speed regulation of automatic extraction or mixed pressure-type turbines is derived with zero extraction or induction flow and with the pressure regulating system(s) inoperative and blocked in the position corresponding to rated extraction or induction pressure(s) at rated power output.

3. *Speed variation*, expressed as a percentage of rated speed, is the total magnitude of speed change or fluctuations from the speed setting. It is defined as the difference in speed variation between the governing system in operation and the governing system blocked to be inoperative, with all other conditions constant. This characteristic includes dead band and sustained oscillations. The speed variation, expressed as a percentage of rated speed, is derived from the following equation:

$$\text{Percent} = \frac{\begin{pmatrix}\text{Change in speed}\\ \text{above set speed}\end{pmatrix} + \begin{pmatrix}\text{Change in speed}\\ \text{below set speed}\end{pmatrix}}{\text{Rated Speed}} \times 100$$

4. *Dead band* is the characteristic of the speed-governing system which is commonly referred to as wander. It is the insensitivity of the speed-governing system and is the total speed change during which there is no resultant change in the position of the governing valve(s) to compensate for the speed change.

5. *Stability* is a measure of the ability of the speed-governing system to position the governor-controlled valve(s) so that sustained oscillations of speed are not produced during a sustained load demand or following a change to a new load demand.

6. *Speed oscillations* are the characteristics of the speed-governing system which are commonly referred to as hunt. The ability of a governing system to keep sustained oscillations to a minimum is measured by its stability.

7. *Maximum speed rise*, expressed as a percentage of rated speed, is the maximum momentary increase in speed obtained when the turbine is developing rated power output at rated speed and the load is suddenly and completely reduced to zero.

The maximum speed rise, expressed as a percentage of rated speed, is derived from the following equation:

$$\text{Percent} = \frac{\begin{pmatrix}\text{Maximum speed at}\\ \text{zero power output}\end{pmatrix} - \begin{pmatrix}\text{Rated}\\ \text{Speed}\end{pmatrix}}{\text{Rated Speed}} \times 100$$

8. *Trip speed* is the speed at which the overspeed protective device operates.

BASIC FEEDBACK CONTROL SYSTEMS ANALYSIS

In order to provide a background in the operation of governors and to relate the previously given parameters to the control theory of governors, a few basic fundamentals of feedback control systems will be presented. The basic objective in an analysis of a governor/prime mover feedback control system is to characterize the control system performance in terms of either the time domain or frequency domain response. The purpose of this section is to examine the performance of a simple governor control system in terms of the time domain response [5, 6].

Basic Automatic Control System

The general components of a basic automatic-control system are shown in Figure 6. Each block in the diagram represents a function which must be performed by the control. The operation may be explained as follows: (1) A command signal θ_i (velocity) is applied to the input and compared with the instantaneous position of the output θ_o (velocity). (2) The result of this comparison ϵ, representing an error, is amplified by a controller and used to position a power element. (3) The power device in turn further amplifies the error signal to supply large amounts of power to the output or load to reduce the difference between velocities θ_i and θ_o.

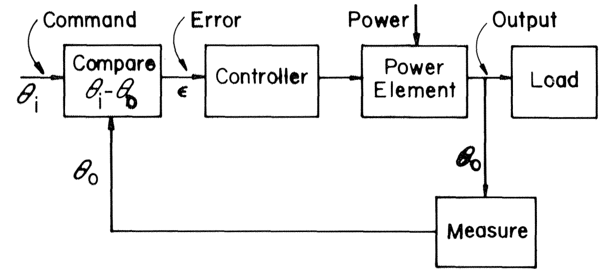

Figure 6. Functional Diagram of an Automatic Control System.

Transient Analysis of A Control System

The stability, accuracy, and speed of response of a control system are determined by analyzing the steady state and the transient performance. It is desirable to achieve steady state in the shortest possible time, while maintaining the output within specified limits. Steady state performance is evaluated in terms of the accuracy with which the output is controlled for a specified input. The transient performance, i.e., the behavior of the output variable as the system changes from one steady state condition to another, is evaluated in terms of such quantities as maximum overshoot, rise time, and response time (Figure 7).

1. *Transient-Producing Disturbances*. An automatic control normally has only two places where disturbances can be expected: at the input or at the load. For a purely mechanical system, the input disturbance may take the form of a periodic oscillation, a displacement, a velocity, or an acceleration. Disturbances at the output are usually load changes expressed as a torque or force quantity. Nonmechanical systems have disturbances expressed in different quantities; however, they are directly analogous to the mechanical system.

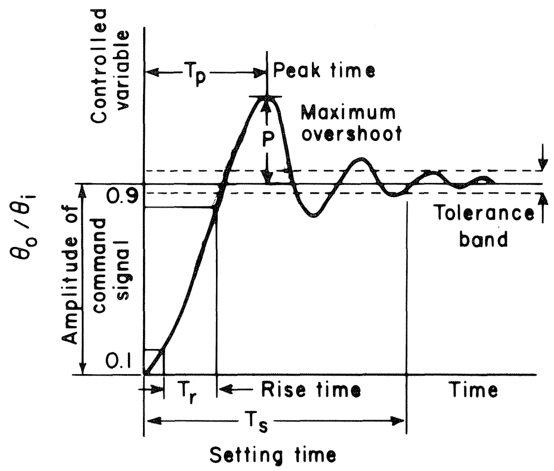

Figure 7. System Response to a Unit Step-Function Command.

2. *The Basic Closed-Loop Control.* To illustrate some characteristics of a basic closed-loop control, consider a mechanical rotational system composed of a prime mover or motor, a total system inertia J, and a viscous friction f. To control the system's output variable θ_o, a command signal θ_i must be supplied, the output variable measured and compared to the input, and the resulting signal difference used to control the flow of energy to the load. The basic control system is represented schematically in Figure 8.

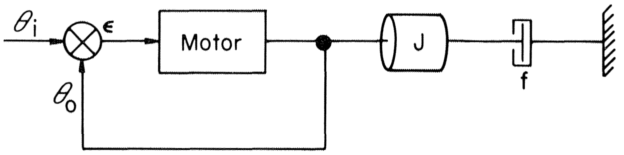

Figure 8. A Basic Closed-Loop Control System.

The differential equation of this basic system is readily obtained from the idealized equations.

$$\text{Load torque } T_L = J\frac{d^2\theta_o}{dt^2} + f\frac{d\theta_o}{dt} \tag{1}$$

$$\text{Developed torque } T_D = K\epsilon \tag{2}$$

$$\text{Error } \epsilon = \theta_i - \theta_o \tag{3}$$

The above equations combine to yield the system differential equation:

$$J\frac{d^2\theta_o}{dt^2} + f\frac{d\theta_o}{dt} + K\theta_o = K\theta_i \tag{4}$$

3. *Step-Input Response of a Viscous-Damped Control.* If the control system described in Figure 8 by equation (4) is subjected to a step change in the input variable θ_i, a solution $\theta_o = \theta_o(t)$ can be obtained as follows:

a. Define the *natural frequency;* $\omega_n = \sqrt{K/J}$

b. Define the *friction coefficient;* $f_c = 2\sqrt{KJ}$

c. Define the *damping ratio;* $\zeta = f/f_c$

Then, equation (4) can be written as:

$$\frac{d^2\theta_o}{dt^2} + 2\zeta\omega_n\frac{d\theta_o}{dt} + \omega_n^2\theta_o = \omega_n^2\theta_i \tag{5}$$

The complete solution of equation (5) is:

$$\theta_o = 1 - \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}}\sin\left(\sqrt{1-\zeta^2}\,\omega_n t + \tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta}\right) \tag{6}$$

Equation (6) is plotted in dimensionless form for various values of damping ratio in Figure 9. The curves of $\zeta = 0.1$, 2, and 1 illustrate the underdamped, overdamped, and critically damped case, where any further decrease in system damping would result in overshoot. Damping is a property of the system which opposes a change in the output variable.

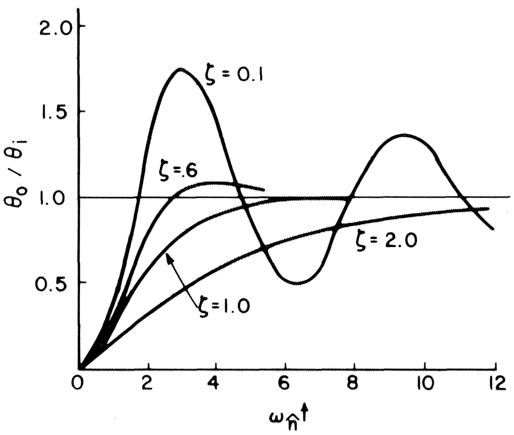

Figure 9. Transient Response of a Second-Order Viscous-Damped Control to Unit Step Input Displacement.

The features of an observed transient performance are a) the existence and magnitude of the maximum overshoot, b) the frequency of the transient oscillation, and c) the response time.

Referring to Figure 7, the following definitions are useful in evaluating the control systems and may be useful in the early design stages of these systems. These equations define the parameters used in the preceeding section.

$$\textit{Rise Time, } T_r = \frac{17.6 - 19.2\zeta}{\omega_n}\ ;\ 0.2 \leqslant \zeta \leqslant 0.75$$

$$T_r = \frac{-3.8 + 9.4\zeta}{\omega_n}\ ;\ 0.75 \leqslant \zeta \leqslant 1$$

$$\textit{Peak Time, } T_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}}$$

$$\textit{Peak Overshoot, } P = \frac{e^{-\pi\zeta}}{\sqrt{1-\zeta^2}}$$

ELECTRONIC GOVERNOR

Electronic Governor Operation

The recent development of the electronic governor has eliminated many of the problems associated with fly-ball governors and high rotational speeds. Electronic governors provide more flexible and more dependable speed control. To measure speed with an electronic governor, a magnetic proximity probe is positioned opposite a toothed wheel on the rotating turbine shaft, see Figure 1. The frequency of the electrical current flowing from the probe is proportional to shaft RPM. The frequency signal is then used in an electronic circuit for an analog or digital speed read-out, and also is compared in another circuit to an electronic set point signal. Should a speed deviation occur, the electronic output signal from the controller will act on the steam inlet valve to restore the set point speed. The controller output is normally a 4 to 20 milliamp current signal. This current is then converted to a 3 to 15 psi air signal, which operates a pneumatic actuator. The actuator moves the inlet steam valve according to the desired restoring motion. The pneumatic actuator is capable of several hundred pounds of force. This is sufficient to overcome any opposing steam forces or valve sticking which may occur.

The electronic governor has several outstanding advantages. The electronic circuits are extremely reliable, requiring very little maintenance. The governor does not touch the shaft. Therefore, high rotational speeds present no problem, since the gear reducer is eliminated. Also, the turbine can be placed on manual control and the governor can be replaced or repaired without shutting down the machine. The electronic governor poses two main disadvantages. If the magnetic probe malfunctions, the resulting loss of signal renders the electronic governor inoperable. Likewise, a loss of electrical power to the governor renders it useless unless backup batteries are provided. When using an electronic governor, provisions must be made to control turbine speed, should loss of signal or loss of power occur. It should be emphasized that an electronic governor will have adjustable droop or no droop, as desired, and no measurable dead band.

Comparison Between Mechanical and Electronic Governor

A direct comparison between the mechanical and electrical governors is shown in Figures 10 and 11 [1]. The mechanical governor, shown in Figure 10, detects the difference between the force generated by the speed demand N_D via spring S1 and the resolved fly-ball centrifugal force, proportional to the achieved speed N_A, as an axial movement at the detector E_1. This mechanical motion is coupled to the speed valve of a hydraulic amplifier K controlling linearly the direction and speed of the integrating ram. The output ram is coupled, via an adjustable position feedback link RV1, to the second detector E_2 and to the fuel regulation valve to modulate the flow of fuel to the engine, and thus its speed N_A.

The electronic governor, Figure 11, compares at its detector $E_1(\theta_i)$ the difference between a voltage proportional to demand speed N_D, set by a potentiometer, and a voltage proportional to engine speed N_A. The detector term is a voltage applied into the amplifier K having an output such that the integrating electric motor rotates at a speed and direction proportional to that output. A second potentiometer connected to the output shaft provides a voltage proportional to position and is applied to the second voltage detector E_2 as a positional feedback via the droop control RV1. The motor output is connected also to the fuel regulating valve in the same way as in the mechanical system (see Figures 6 through 9 for reference).

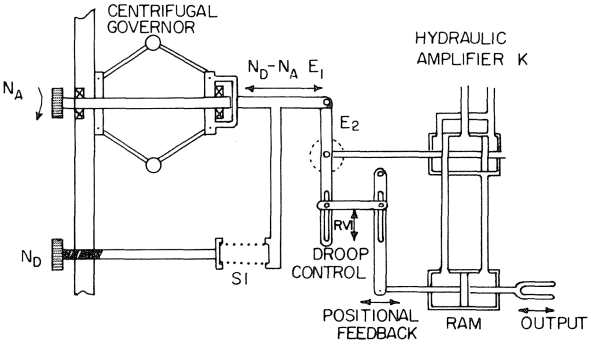

Figure 10. Hydro-Mechanical Speed Control System.

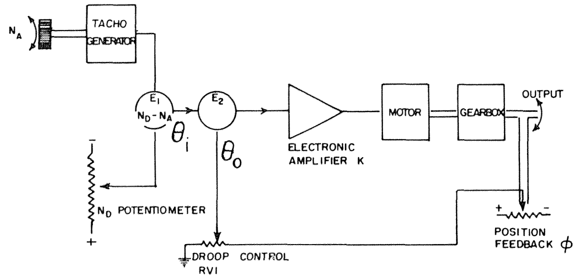

Figure 11. Electronic Speed Control System.

The basic analysis presented in the previous sections applies to either type of system, because there are similarities in the two types of governors. However, where designing for system application, there are many differences, as will be addressed in the following sections.

COMMERCIAL ELECTRONIC GOVERNOR DEVELOPMENT

Industrial Development and Application

In the early 1970's a few industrial users of turbines moved into the development and manufacture of electronic turbine speed governors to replace the unreliable conventional type governors on various turbine drives. The industries that began using some type of electronic control scheme either developed their own hardware or worked with a specific control manufacturer to develop the necessary components.

Some manufacturers and users of turbines have developed the in-house technology through research and development with their on-line production turbines. Also, other specialized companies, such as Woodward [7], Vevey [8], Tri-Sen [9], Barber-Coleman [10], General Electric [11], and others, have extended or developed their governor systems to incorporate the advantages of the electronic controls. Woodward and General Electric have developed their electro-hydraulic line of governors to help meet the need for control of paralleled generator sets. One of the main requirements for electric governors occurs when isochronous operation of paralleled generator sets is needed. Their systems operate so that, when the electric load on each generator is measured, the signals are sent directly into the electronic governor circuit to balance the load between the paralleled generator sets. Tri-Sen has developed a complete electronic control package for drive systems. Their electronic governors will provide precise speed control for any industrial turbine or engine that can be controlled by a single actuator. Barber-Coleman provides a precision electronic governor that measures three engine parameters to provide precise engine control. Separate circuits measure the proportional (amount of offspeed), integral (time of offspeed) and the derivative (rate of change of offspeed) values of the input signal. These three circuits produce an output that results in fast, stable engine response to offspeed changes.

These are a few of the characteristics that electronic governors provide. However, these governor manufacturers, as well as several others, can provide many other options for turbine/engine control. The above comments were made to illustrate the type of control characteristics available.

The details of the various electronic governors will be discussed later. The question that is asked now is what led the users to develop, or to have developed, an electrically powered governor. It appears that some of the main reasons were:

1. To provide control for the isochronous operation of paralleled units.
2. To eliminate the coupling of the governor to the rotating shaft.
3. To provide improved transient response control.
4. To provide temperature and compressor discharge pressure control.
5. To provide better fuel management during startup.
6. To incorporate more flexible and compact mounting arrangements to governor units.

Again, these are a few of the reasons for moving toward the implementation of electronic governors. However, if electronic governors are to be used by industry, there are several needs that must be satisfied by the governors for satisfactory operation. Several of the features/goals outlined by industrial users for electronic governor development are [12, 13]:

1. Local and/or remote speed set capabilities. Selection of local or remote set should be bumpless and switchless such as selection of the highest signal.
2. Remote start/stop capabilities utilizing some form of acceleration control on startup to prevent overspeeding.
3. Provide accurate speed control to prevent system oscillation or vacillation (hunting).
4. Provide reliable electronics.
5. Provide tachometer readouts, both remote and local (either digital or analog).
6. Provide redundant logic in transducer components. For example, one out of three transducer failures should be able to occur without shutdown. This type of logic is directed towards preventing false loss of control or false tripping of system.
7. Provide replacement of faulty transducers without turbine shutdown. For electromagnetic sensors, this requires a) replacement without control default, b) replacement access in turbine hardware, and c) proper gapping to a tach wheel with concern for both safety and performance of the transducer.
8. Should operate from virtually any power source, drawing minimum current, including integral battery backup capabilities.
9. Provide controls through dependable hydraulic servo controls and pistons since the control linkage offers high resistance and inertia from weaker systems.
10. Extraction admission steam control in either flow or pressure control modes.
11. Load sensing and paralleling capabilities for generator applications.
12. Controls from a control house or local panel should be possible, generally with a lock-out capability so that both are not in service simultaneously. This would allow the turbine to be controlled in either manual or automatic mode from the barring speed to the design speed from the control station. It has always been a deterrent to have to manually bring a turbine to some minimum governor speed, engage the governor system (manually or automatically) and proceed on to a minimum or maximum operating speed.
13. Provide process control capabilities to allow multivariable input and control functions. These might include load, suction and/or discharge pressure, steam back-pressure, inlet steam pressure, and process flow control as well as speed control. They should be able to be implemented as an output restraint (either high or low), or as a multi-input auto selector system.
14. Provide a mechanical overspeed protection backing up the electrical overspeed.
15. Provide removal of the various mechanical appendages that negatively affect the turbine rotor response, i.e., shaft extensions, step down gearing, and any overhang preloads.

These goals not only outline areas needed for present and future developments, but they also present a view of the industrial user's needs in governor controls.

Industrial Applications

The following discussion is presented to show a typical industrial application/development situation by a user of the electronic governor. There are many other similar cases where industrial users have started using the electronic systems, and the following example is given to illustrate the type of conditions that exist in industry as a result of adopting the electronic governor.

During the first part of the 1970's, a Texas refinery made the decision to develop some type of electronic speed governing device to replace the unreliable mechanical-hydraulic governors on various drive systems. While they only replaced those governors which had caused considerable difficulty, the success of the electronic components over the succeeding six years had expanded the total installations to nearly the 300,000 hp level on over 60 machines. The combined operating time of those governors exceeded 100 years.

Three basic types of governors were developed at this refinery:

1. Gas Turbine/Steam Turbine Governor: A complex governor system designed to control a steam helper turbine and gas turbine in tandem. This governor sensed and correlated several parameters of the gas turbine such as speed, air pressure, and exhaust temperature to accurately and effectively control the operation of those units.
2. Multi-Rack: Basically the complex rack steam turbine governor system was removed and expanded slightly to regulate the large multivalve steam turbines in the refinery by sensing several parameters. There were twenty-one governor installations of this design, including four outside the refinery.
3. Single Rack: A single rack unit designed to replace all the mechanical governors on small to medium-sized turbines in critical service. The device consisted of a printed circuit board

containing all electronic components mounted inside a Fisher transducer body. It was mounted at the turbine and required no special mounting provisions, other than the installation of a standard diaphragm operator or control valve to control steam flow. There were thirty-six installations of this design (see Figures 12 through 14). All of these governor installations have offered marked improvement in reliability and accuracy of the operation of the equipment.

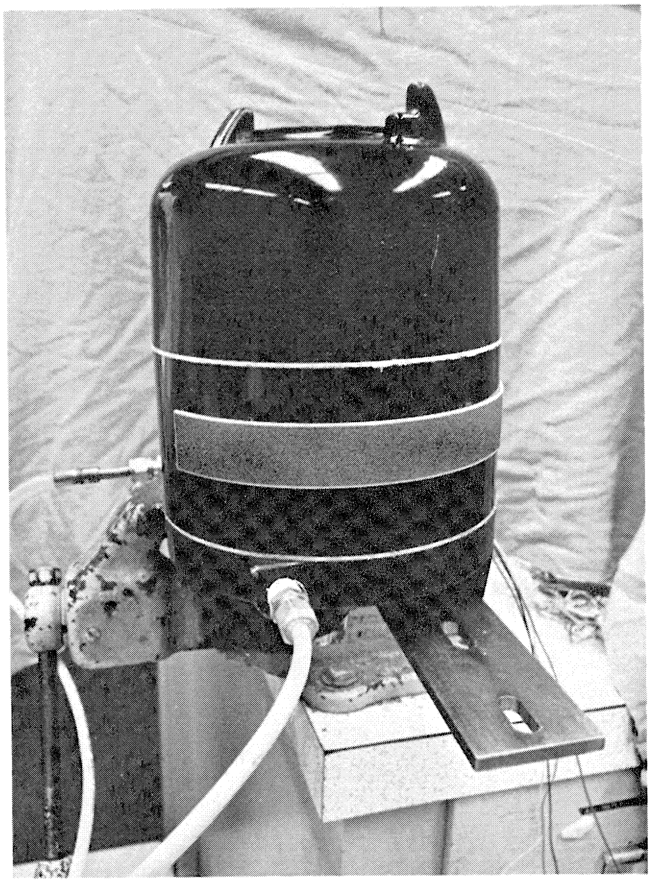

Figure 12. Typical Electronic Governor Enclosure.

This concept of providing advanced technology and reliability with a minimum of operator attention has proven highly successful and this refinery's system reliability has been much, much higher. At the time these control units were being developed, the multi-rack system had only one direct competitor on the market. The competitor's unit did not have all the features of the single-rack design and the competitor's transducer that converted the electronic signal to hydraulic operation had proven to be unreliable in the developer's experience and that of numerous other users. The single-rack governor had no direct comparable governor other than a small, custom-made, all-hydraulic, self-contained governor. The light and delicate turbine governor valves became fouled with steam deposits, requiring a greater pushing force than this comparable governor could develop. While the single-rack governors were dependent upon two utility supplies, the 48 VDC operating power (unit switch gear battery bank) and instrument air, it was found that their improved reliability more than offset the increased dependency upon outside power sources.

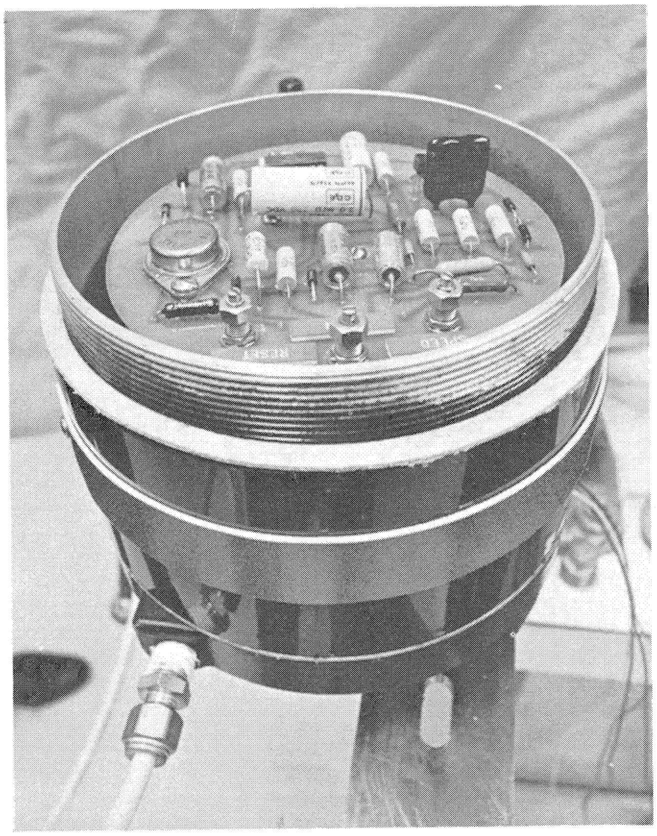

Figure 13. Electronic Governor Printed Circuit.

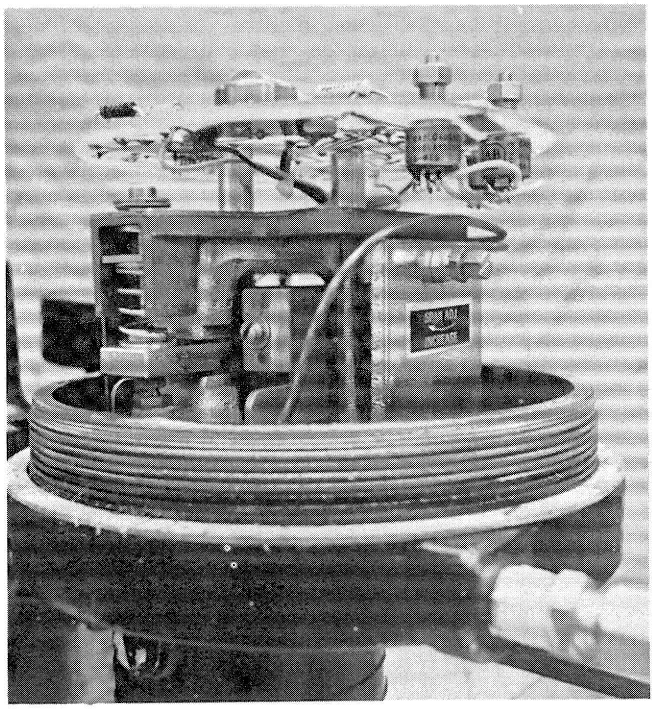

Figure 14. Electronic Governor Circuit with Actuator.

Applications of the turbine governors had been made to virtually all of the manufacturer's equipment with no significant difficulties. This included reciprocating engines. While the equipment had to be custom-tailored to the installation, most of this tailoring involved the mechanical features of the turbine and required limited redesign of the electronic components. The printed circuit control could be quickly replaced with the turbine running, with a spare card from stock. To date, most of the installations made at the refinery have been on very troublesome machinery maintenance-wise. The excellent results and wide acceptance of these speed control devices should encourage others to seek out and upgrade their equipment which can benefit from such improvements.

Typical Electronic Governor Installation

The electronic governor provides precise speed control of any industrial prime mover that can be controlled by a single pneumatic actuator and provides excellent performance and reliability.

Figure 15 shows a typical installation of an electronic governor on a steam turbine; however, the unit can be applied equally well to any steam or gas reciprocating engine. The input is usually a speed signal from a conventional magnetic pickup. The output is a 3-15 psig signal used with a standard pneumatic actuator.

Refer to Figure 16 for a block diagram of a typical system. The speed measurement signal is usually generated by a magnetic pickup in proximity to a toothed wheel or gear mounted on the turbine shaft. The pickup outputs a signal with a frequency proportional to speed which the governor converts to a precision DC voltage to drive the tachometers and provide the governor measurement. Other devices, such as proximity probes, can also be used as the frequency input. A dual pickup option allows the governor to function on either one of two inputs.

The governor electronics are mounted on two circuit boards inside a high quality electric-to-pneumatic transducer, see Figure 14. One board, called the "main board," contains the governor electronics. The other board, called the "option board," contains the power supply module and the overspeed/underspeed trip options.

The transducer is mounted on a panel with another enclosure called the "control station." The control station contains the start and stop push buttons, the local speed set, the local tachometer, the trip relay, the trip light, the pneumatic speed set transducer, and a termination board. The control station can be supplied for Division I or II hazardous locations. The whole unit is light, compact, self-contained, and is usually mounted at the turbine or engine on a simple 2″ pipe stand. Figure 17 shows a typical governor suitable for Division II hazardous locations. Figure 18 shows a typical installation. The final actuator can be any pneumatically operated valve or assembly controlling the steam or fuel to the machine, as shown in Figure 19.

All the control functions are reduced to a single unit; and in many cases, troublesome and complicated gearing arrangements, linkages, and hydraulic equipment are eliminated. Electronic governors are not the addition of equipment to an already complicated system. They replace existing equipment with simpler, more reliable equipment with more features and better performance.

Performance

The electronic governor will control speed over any desired speed range with a typical steady state speed regulation of 0.1% of rated speed. Analog tachometer accuracy is ± 1% of full scale and the digital tachometer will read 0.01% of reading ± 1 digit. Speed can be changed over the governor range by a calibrated dial or any standard process control signal, or both, with a 0.1% accuracy. If a local and remote set point options are used, the one calling for the highest speed will control. Table **II** lists the basic performance characteristics of several commercially available governors.

A wide range of adjustable reset and gain controls allow the unit to be tuned for excellent response and machine stability. Under optimum conditions a 50% load change will temporarily change speed less than 5% with recovery to set point in less than one second. However, this will vary depending upon the type of actuator used and the machine dynamics. Using acceleration control (batch control) during startup allows a machine to automatically go from idle at no load to rated speed and load in three or four seconds without overshoot.

Reliability

There are several features of the electronic governor that make it very reliable [13].

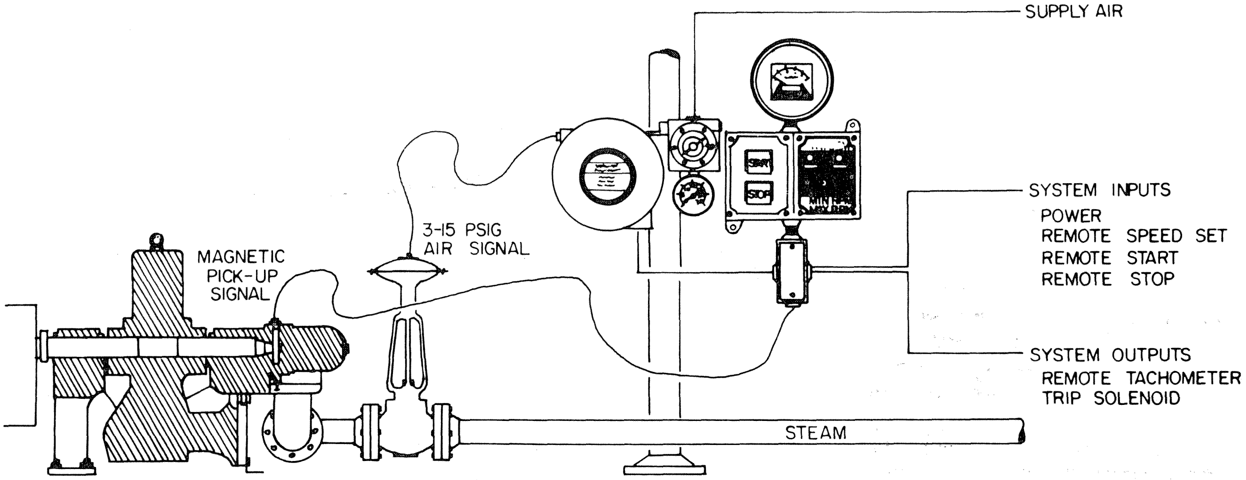

Figure 15. Electronic Governor Installation.

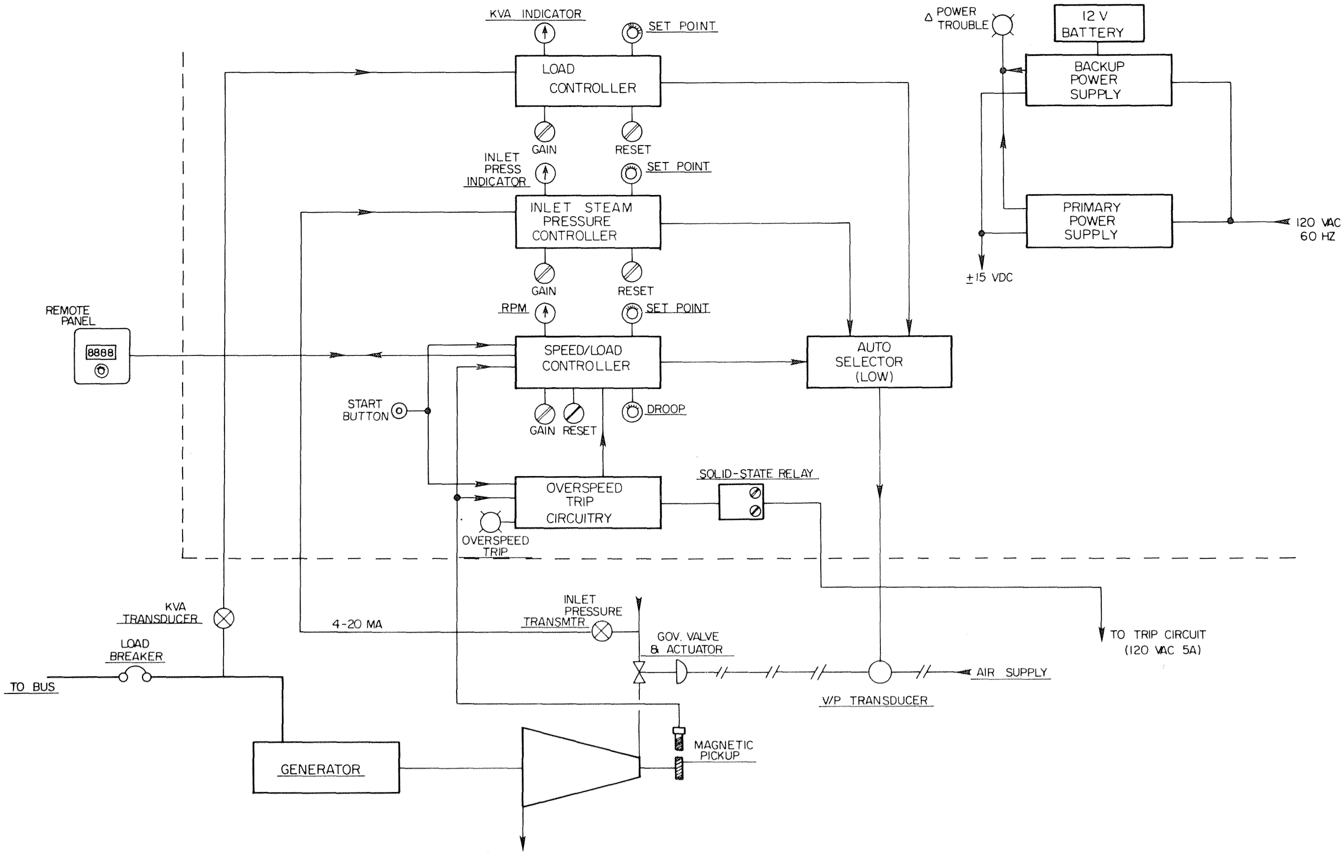

Figure 16. Schematic of Typical Electronic Governor System.

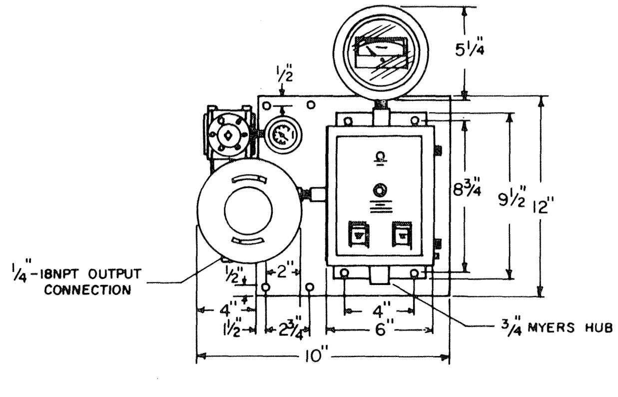

Figure 17. Electronic Governor Package.

1. Solid state electronics are inherently reliable, and in the continuously purged environment inside the transducer housing, the circuitry will function maintenance free for years. One user has seven years' experience on several hundred governors, without a shutdown due to an electronic failure, as evidence of their reliability.

2. There are no moving parts, other than the final actuator, to wear out and cause downtime for maintenance. The electronic governor is not coupled to the rotating shaft. This means that if a handjack or bypass is provided for the governor valve, the machine need never be shut down to repair the governor.

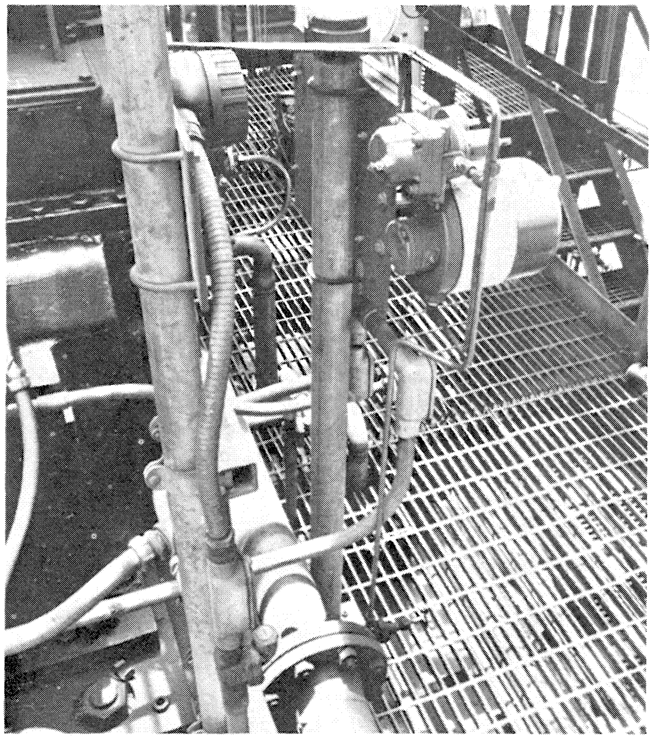

Figure 18. Typical Electronic Governor Installation.

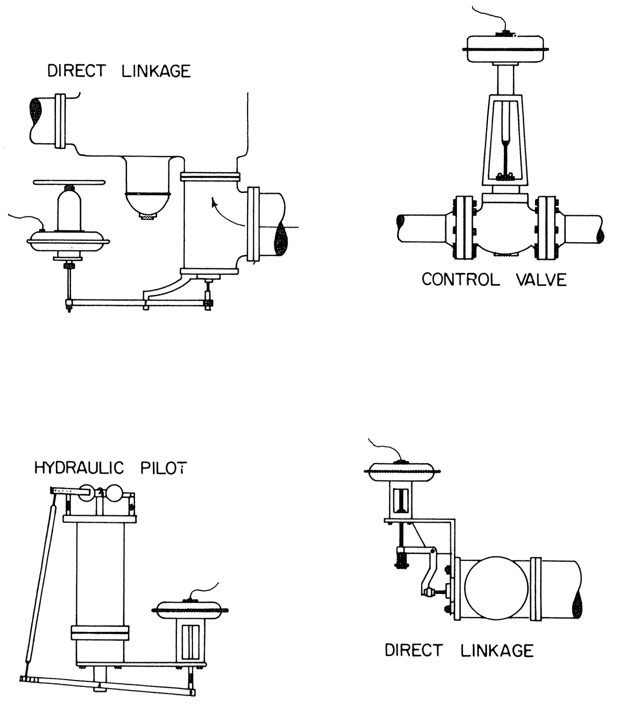

Figure 19. Typical Actuator Installations.

3. A dual pickup option allows the governor to operate from either of two pickups. Should a pickup fail, the governor will continue to operate from the other and give a pickup failure indication so that the bad one can be replaced. If the pickups are externally accessible, they can usually be replaced and adjusted without shutting down the machine.

4. "Failsafe" circuitry shuts the machine down if the governor loses the speed signal. This feature is bypassed for startup to allow the machine to start rolling after the start button is pushed. This assures that the machine is not operated without governor control.

5. An optional overspeed and/or underspeed trip, using the same pickup as the governor or a separate pickup, will close the governor valve and actuate a relay for use to operate alarms, solenoid valves, or other trip devices. The overspeed trip point can be set very accurately without running the machine, and since there are no moving parts to wear or stick, reliability and repeatability are greatly improved over mechanical units.

6. Mechanical governors have relatively low outputs to operate the final control device. Wear of the linkage and valve or deposits on the internals of the valve will cause sticking problems. The high power output of the pneumatic actuator used with the electric governor will usually eliminate this problem.

7. The electronic governor's dependency on electrical power is one of its few disadvantages, and steps have been taken to minimize the problem. Most governors will operate from almost any power source: 120 VAC, 12 VDC, 24 VDC, 48 VDC, etc. Typically, they consumes less than 1.5 watts so they can be connected to any reliable instrument supply or emergency system with negligible drain. Most systems are also available with integral battery options to assure continued operation in the event of a power failure.

Many electronic governors have been in service since installation without maintenance or failure. As an example, an electronic governor installed in 1971 is still in service without a failure.

Most electronic governors are completely solid state and require no routine maintenance as such. They should be inspected periodically for loose covers and fittings and the mounting checked. If problems are experienced with these

TABLE 2. ELECTRICAL GOVERNOR PERFORMANCE CHARACTERISTICS.

Performance Characteristics	Barber-Coleman DYNA I	GE MDT-80	Woodward 2301	TRI-SEN M-300
Power Supply	12-32 VDC 70 Watts (S.S)	4-20 MA, 10-50 MA 1-5 VDC, −10 to +10 VDC	65 Watts (S.S)	−12 VDC to 48 VDC 120 VAC
Input Signal Frequency Range	250Hz-9.5KHz	150Hz-15KHz	450Hz-21KHz	200Hz-10KHz
Adjustable Speed Range, %	0-15%	5-120%	0-10%	0-50% Proportional Band
Maximum Steady State Speed Regulation, % (Isochronous)	±.2%	±.1%	±.25%	±.1%
Maximum Speed Variation, %	±.1%	±.1%	±.1%	±.1%
Maximum Speed Rise, % (Unloading)	±3%	±4%	±2%	±2%
Trip Speed, % (Above Rated Speed)	10%	10%	10%	10%
NEMA Classification	NEMA D	NEMA D	NEMA D	NEMA D

governors, the problems are usually with the speed sensor or the final actuator. Adjusting the final actuator so that it properly positions the fuel valve and maintaining the linkage in proper working order are very important. If the speed sensor and final actuator are operational and the electrical and air supplies are present, then problems with the electronics can be solved by simply replacing the plug-in circuit boards. This can be accomplished in only a few seconds and, if a control valve with blocks and a bypass is used, it can be done without shutting down the machine. A pneumatic manual station between the governor and control valve will allow the same flexibility. In some cases, downtime and maintenance cost can be reduced as much as 50% over a two- or three-year period by use of the electronic governor.

Energy Savings

Substantial energy saving can be achieved by use of the electronic governor. Some savings are direct fuel savings and others are indirect savings achieved by better performance and increased reliability. Direct savings include:

1. Less horsepower to drive the governor.
2. Better efficiency because of less wear on the prime mover.
3. Decreased fuel usage because of more stable operation.
4. Governors on process control allow machine speed to vary to maintain a process variable instead of using less efficient methods such as discharge throttling, etc.

The electronic governors typically use less than 1.5 watts of electrical power and the supply air requires less than one-tenth of a horsepower to produce. Hydraulic and mechanical units can use as much as 1 horsepower to drive the governor and additional horsepower to drive a gear box used to adapt the governor to the machine. This power is obtained from the machine through some type of gearing arrangement on the end of the shaft. This load can cause increased bearing and gear wear which increases loading and vibration, thus reducing efficiency and increasing maintenance. Continuous swinging of the governor valve will have a similar affect.

The speed of a machine is sometimes held constant or the governor valve is held in a fixed position; and bypass valves, discharge valves, flare valves, etc., are used to adjust the load to the machine. It is much more efficient to change speed to accommodate load changes. This is readily achieved with the electronic governor since it will accept any signal from a process controller as a speed set point. This allows the speed to be varied over the governor range to maintain a process variable instead of wasting the process material or artificially increasing the load.

Performance Comparison with Mechanical Governor

1. Advantages

Electronic governors find primary application as a replacement for mechanical governors in applications requiring better speed regulation, increased reliability, and greater flexibility. They have the following distinct advantages over mechanical governors.

a. They are not mechanically coupled to the rotating shaft. This means that, if a hand-jack or bypass is provided for the governor valve, the turbine need never be shut down to repair the governor.

b. All of the electronics for the electronic governors are on plug-in printed circuit boards, so most repairs are confined to plugging in a replacement board which takes only a few seconds.

c. The fact that there is no mechanical governor or reduction gearing on the turbine shaft often results in lower vibration and less bearing wear.

d. The output from the electronic governors is typically a 3-15 psi range pneumatic signal which, when used with a diaphragm actuator, provides high power to operate the governor valve direct or to position the rack via the hydraulic system. It is also readily adapted to many types of hydraulic servomotors.

e. The electronic governors have many standard features, such as tachometer outputs, automatic start/stop features, wide range adjustable set points, etc., that are not readily available with mechanical governors.

f. With the electronic governor changes in speed range, gear teeth, governor range and trip points are easily and quickly accomplished in the field.

g. Finally, the electronic governor will provide a level of performance and reliability not achievable with mechanical units. A setting accuracy of .1% allows them to be set with greater accuracy than many tachometers are capable of reading. Its reliability has been demonstrated in the field to be outstanding.

2. Disadvantages

Disadvantages of the electronic governor are that they do require a power and an air supply, and the governors are only as reliable as these supplies. However, the systems may be readily powered from any available battery supply. These techniques make the governors independent as far as electrical power is concerned. The loss of instrument air supply will render the governor inoperative; however, most industrial installations are already committed to maintain instrument air, so this requirement does not usually present a problem.

CONCLUSION

The foregoing discussion has been presented in order to provide some insight into the usage of electronic governors. The electronic governors with their unique packaging and features have demonstrated impressive performance and reliability. This performance and reliability has reduced maintenance cost and downtime, increased efficiency and operating factors, and opened up opportunities for significant energy savings.

Because of the increasing need for energy conservation and engine performance, industry will be looking for techniques for assisting in their conservation measures. The electronic governor will be playing a much stronger role in this effort in the future.

ACKNOWLEDGEMENTS

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