8.0 DIESEL ENGINE CONTROLS AND GOVERNING

This chapter presents the principles of the governing system which controls the power output by the engine. It is the electrical demand on the generator that sets the load demand on the engine. The governor controls the fuel to the engine to establish the speed of the engine, and thereby the frequency of the generator.

<u>Learning Objectives</u>

As a result of this lesson, you will be able to:

1. Describe the functional relationship between the engine control governor and the fuel injection system.

2. Explain how the engine control governor senses changes in the generator load or demand and compensates by regulating the fuel delivery to the diesel engine.

3. Describe the primary components of the governing systems used on diesel generator set engines used in nuclear applications.

4. Explain how the terms isochronous and droop apply to the diesel generator set engines used in nuclear applications.

8.1 Control Fundamentals

8.1.1 Diesel Engine to Generator Relationship

In the application of Emergency Diesel Generators (EDGs), the primary objective is to provide the electricity needed to operate the plant safety-related systems, allowing operators to achieve and maintain a safe shutdown condition.

EDGs consist of two physically and functionally related components. The driven component, the electric generator, produces the power required to safely operate plant systems in the event of a loss of the plant primary power sources. The driving component, the diesel engine, converts energy supplied in the form of fuel oil into mechanical energy. During operation of the EDG, the power (voltage and current) produced by the generator is regulated by the generator excitation system.

As discussed in Chapter 4, the power output of the diesel engine, and consequently the power input to the generator, is controlled by regulating the quantity of fuel delivered to the engine cylinders. In turn, the regulation of the fuel is controlled by the engine control governor.

The relationship between the generator output frequency and the engine speed is expressed by the formula:

$$F = N * P / 120$$

Where F is frequency, N is the engine speed in RPM, and P is the number of poles on the generator. A 900 rpm engine requires an 8-pole generator to produce 60 Hz power. For 60 Hz, use the following: $N = 7200/P$ (therefore, $P = 7200/N$)

8.1.2 Governor Principles

Chapter 4 discussed the very basic principles of the governing of the engine through a system that controls the amount of fuel delivered to the engine cylinders through the control of the fuel injection equipment on the engine. This section will expand upon the governing system aspect of the engine control system. The governing system monitors the speed and/or load on the unit and regulates the fuel injection system to attempt to hold the speed or load on the unit constant. We will explain how this is done in a number of different systems that are used on diesel engines in nuclear plant applications.

8.1.2.1 Isochronous-Droop Relationship

Every governing system and governor type has to contend with a problem of the control of a generator when it is connected into a large system with other generators. A very large system is often referred to as an 'infinite bus' or 'the grid.' Some means must be provided to allow control of a single machine while paralleled with other machines.

Two terms have come into usage for describing the requirements of control in a governing system. The first is 'isochronous;' the other is 'droop.' The word 'isochronous' can be broken into two parts – 'iso' meaning 'equal' and 'chronous' relating to 'time.' As applied to an engine, isochronous means that each revolution of the engine takes an equal time, or in other words, the speed is constant. 'Droop' indicates that something is falling off or drooping. As applied to a generator set, it means that as load is applied the speed falls off or diminishes. The following explains how these terms are applied to the diesel generator and why droop is required.

If the diesel generator is operating all alone on an electrical system and is not in any way connected to other generators, it is most desirable to have the generator maintain its frequency (speed) regardless of the load it is carrying. In other words, it should be 'isochronous.' However, if that same unit were put on a system with other generators, and particularly if there were many other generators and a very large system (infinite bus), there is a potential problem. If the new unit's frequency (speed) is even a small amount higher than the system frequency, the new unit will attempt to bring the system up to its frequency. The only way it can do this is to attempt to carry the whole system load. This would result in the new unit being overloaded, and could damage it.

If the new unit's frequency (speed) is just a little lower than the system frequency, the system will attempt to bring the new unit up to the system frequency. The only way the system can do this is to drive the new unit or in other words, to motorize the generator in order to bring the unit up to the system frequency. Since the unit will now be running at a speed that is above its governor speed setting, the governor will back off the fuel and the unit will simply operate as a motorized unit. This is not harmful to the generator nor the engine providing that fuel flow is maintained to the fuel injection components such that they are lubricated. The term 'reverse power' is applied to this condition, and it will be discussed further in Chapter 10, "Emergency Diesel Generator Control and Monitoring."

Droop in a governing system is defined as the change in speed the unit makes in going from 100% load to no load. By definition, it is the difference between the no-load speed and the rated speed, divided by the rated speed, all times 100 to obtain the percent change.

$$Droop = \frac{(noloadspeed - ratedspeed) * 100}{rated\ speed}$$

One means of determining the droop is to run the unit at 100% load with the speed adjusted to 60 hertz. Trip the load breaker open, and the unit will end up at a higher speed. This is the no-load speed. Apply the formula above to compute the percent droop.

To prevent the unit from being either overloaded or motorized, droop is introduced into the governing system. As the engine is loaded, the speed/frequency tends to drop off (droop). Since the unit is locked into the grid, it cannot change speed, but that is what the droop in the governor would attempt to do.

To best explain how droop is used in the system, refer to Figure 8-1. In this diagram, the right ordinate axis represents the grid frequency. The left ordinate is the reference speed input (the point to which the operator wants the unit to run). The abscissa is the percent loading and goes to 110% in as much as most EDG units will have an 'overload' rating.

If the unit is running in ‘isochronous’, the right and left ordinate values are the same with the load line being flat and having no slope (parallel to the base of the graph). The operator sets the unit at the desired speed and the unit operates at that speed for all loads (with only short durations of off speed during the actual load change and the unit's subsequent recovery time).

If the unit were operating alone (on an isolated system) with droop, then the operator would dial in the desired speed. As the unit were loaded, the speed would drop. To compensate for the speed drop, the operator would have to continuously adjust the speed reference up in order to arrive at the rated speed at 100% load.

Two lines are shown on the chart going through 100% load and rated speed (60 hz) - one for 3% droop (solid line) and one for 5% droop (dashed line). Note that the speed reference is now at 61.8 Hz and 63 Hz respectively for the 3% and 5% conditions.

Since the operator cannot change the system speed, his only means of loading the unit against the system-maintained speed is to change the speed reference setting. Another solid line for 3% droop shows the setting for 50% load. This is what is done when a unit is synchronized to the system in order to manage the loading of the unit. After synchronizing the unit and closing its breaker, the operator must adjust the speed reference input (through the motor operated potentiometer or other means) to have the unit take on load or to decrease the load.

Once the unit is on the system and loaded to the desired load, the unit will not change load unless the operator changes the speed reference input. However, if the system frequency were to change by a small amount, the load would also change by some small amount as shown by the two lines close to, and parallel with, the 60 hertz isochronous line.

8.1.3 Governor Classifications

8.1.3.1 By Design and Construction

Mechanical governors: In mechanical governors, the output or controlling force is created by centrifugal force acting on a set of rotating weights. Because the weight assemblies are relatively small, the output force is not sufficient to control the injection pumps on large engines. Mechanical governors are limited to use on small and automobile type diesel engines. A simple diagram for a mechanical governor is shown in Figure 8-2.

Hydraulic Governors: With hydraulic governors, the rotating weight assemblies connect to a control valve rather than directly to the fuel control racks. The control valve directs hydraulic fluid to or away from a power piston. The power piston, in response to the hydraulic fluid, controls the fuel racks and therefore the engine power or speed. In this way, a greater force is available to move the fuel racks on medium and large size diesel engines. A simple diagram for a hydraulic governor is shown in Figure 8-3

Electric-Hydraulic Governors: The electric-hydraulic governors normally utilized in nuclear service have a governor actuator with two sections–a mechanical hydraulic backup governor and an electric governor. If the electric governor were to fail, it is possible to run the unit on the mechanical hydraulic backup governor under manual control. In normal operation, the mechanical hydraulic backup governor is set at a speed above the rated speed, and the electric governor is used to control the unit. The electric governor has control of both the load and speed of the governor system. A view of a typical electric-hydraulic actuator is shown in Figure 8-4. The actuator is the interface between the electrical portion of the governing system and the engine (mechanical portion). An example of this scheme is shown in Figure 8-5.

An electric control valve is connected to an armature in an electromagnetic field. An electric control box sends a signal to the field which positions the armature and, therefore, the control valve to regulate the fuel delivery. When operating in the electric mode, the electric control overrides the mechanical hydraulic control. In this way, the diesel engine operates in response to the demand on the emergency generator.

Detail of the governor actuator and the electric governor are explained in more detail later in this chapter.

8.1.4 Principles of Operation

The following three sections discuss the basic principles of governor operation.

8.1.4.1 Flyweight Assembly

Virtually all governors are equipped with a rotating flyweight assembly as shown in Figure 8-2. Two or four individual flyweights are mounted on the rotating ballhead. The ballhead is driven by the engine through a drive gear assembly. The speed of the ballhead is directly proportional to the engine speed.

As the ballhead rotates, centrifugal force acts on the flyweights forcing them outward. The amount of force exerted on the weights is a direct function of the engine speed. The higher the engine speed, the higher the force exerted on the flyweights. The speeder spring is installed to counteract the force of the flyweights.

With mechanical governors, the flyweights connect to a control sleeve which in turn connects to the injector fuel control racks. With the engine operating at a constant speed and load, the force on the flyweights is exactly balanced by the force of the speeder spring.

If the load demand on the engine is increased, the engine tends to slow down. As the engine slows, the force of the speeder spring overcomes the force of the flyweights and the control sleeve lowers. Lowering of the control sleeve causes the fuel control racks to increase fuel delivery and therefore the power developed by the engine. With the increase in engine power, the engine returns to the desired rpm, and the forces of the speeder spring and flyweights again balance.

If the load demand on the engine is reduced, the engine speed tends to increase. The increased speed increases the force exerted by the flyweights which now overcome the force of the speeder spring, raising the control sleeve. This movement of the control sleeve reduces the fuel delivery and the engine power to cause the engine to return to its steady state rpm.

There is in this mechanical scheme an inherent droop. The only way that the increase in fuel necessary to support an increase in load is maintained is to have the output control stay in the same position. But, the only way to maintain that position is to have the engine operating at a lower speed. Therefore, there is always droop in this system.

8.1.4.2 Hydraulic Controls

With the hydraulic governor, the fly-weights connect to a hydraulic control or spool type valve as shown in Figure 8-3. Hydraulic oil is supplied to the control valve by a small gear pump mounted in the base of the governor. A power piston is hydraulically connected to the fuel control racks. A spring acts on the power piston to oppose the hydraulic force. The bottom of the control valve sleeve is open to the oil sump in the bottom of the governor housing.

At a constant speed and load, the control valve is positioned to block the ports in the valve sleeve which creates a hydraulic lock to the underside of the power piston.

An increase in load causes the engine to slow down. The flyweights move in when the levered force exerted by the flyweights falls below the force exerted by the speeder spring. This action lowers the control valve which directs the oil pressure supplied by the gear pump through the sleeve to the underside of the power piston. Upward motion of the power piston moves the fuel racks to increase fuel delivery and return the engine to its steady state rpm. As this happens, the control valve raises to again take the neutral or blocking position.

The hydraulic governor acts as a mechanic/hydraulic amplifier. A small mechanical input can produce an output force, created by hydraulic pressure, sufficient to control the fuel racks with a higher degree of sensitivity than is possible with a mechanical governor.

Because there is no longer a direct relationship between the power piston position and the control valve position, this system eliminates the ‘droop’ inherent in the strictly mechanical governor.

8.1.4.3 Electric Controls

Within actuators used on EDGs in nuclear power plants, there is both a mechanical-hydraulic governor and an electrical-hydraulic section that is operated from the electrical governor control unit. There are two different systems being applied to these EDGs. One system is an older obsolete system referred to as the EGA control. The newer unit is the 2301A control. In this section, we will discuss the actuators used in both systems.

8.1.4.3.1 EGA Actuators (Figure 8-5A)

Depending upon the size of the engine, the EGA actuator will be either the EGB-10C (used on the FME OP engines and ALCO units), the EGB-35C, or the EGB-50C (used on the FME Pielstick engine units). The numerical value following the EGB signifies the maximum work effort (in foot pounds) that the actuator can produce in moving the engine fuel controls.

In addition to the backup hydraulic governor with its control valve, the electric-hydraulic governors uses a second control valve connected to an armature magnet in a variable electro-magnetic field as shown in Figure 8.5A. A set of centering springs are used to center the armature in the field with the control valve in the blocking position.

An electronic governor control box (EGA) monitors the output of the generator for both load and frequency. The control box generates a signal which is applied to the field coil in the governor actuator housing. An increase in load demand or decrease in speed causes the control box to generate a signal which lowers the armature magnet and control valve. Oil pressure is now directed to the underside of the power piston, raising the power piston and increasing the fuel delivery. The engine returns to its steady state mode, and the control valve is returned to the blocking position.

With a decrease in load demand and/or increase in speed, the control box raises the armature magnet and control valve. The oil under the power piston is now drained to the governor sump, and the spring pushes the power piston down. This reduces the fuel delivery and engine power to return the engine to its steady state condition.

Actually, there is a small bias voltage put out by the control box when the control valve is centered (in the blocking position). This is to cause the electric governor section to go to the full fuel position in the event that the electric control box fails. This causes the actuator to go to the mechanical hydraulic actuator higher speed setting until normal operator action is taken to reduce the speed setting to the desired control point. Only one of the governor actuator sections may be in control at one time; otherwise, governor instability can result.

8.1.4.3.2 2301A Actuators (Figure 8-5B)

Depending upon the size of the engine, the 2301A actuator will be either the EGB-13P (used on the FME OP engines and ALCO units), the EGB-32P or the EGB-50P (used on the FME Pielstick engine units). The 'P' suffix indicates a proportional actuator system.

The actuators used with the 2301A governing system are proportional systems. That is, the governor output is proportional to the electrical input from the 2301A control. On the EGA actuator, the output was only as required to close the actual speed to commanded speed loop.

In addition to the backup hydraulic governor with its control valve, the electric-hydraulic governors use a second control valve connected to an armature magnet in a variable electro-magnetic field as shown in Figure 8.5B. However, in addition to the centering springs is a lever system that biases the transducer in proportion (in relation) to the position of the electrical portion power piston. This causes a feed back into the 2301A control such that it knows about how much fuel is going into the engine for a given load and speed condition. The output signal from the 2301A control therefore becomes proportional to the load on the unit and the fuel requirement to support that load or speed.

Other than that difference, the remainder of the 2301A actuator works essentially the same as the EGA actuator, as described above.

A failure of the electrical signal from the 2301A control causes the electric governor section to go to the full output position. This causes the actuator to go to the mechanical hydraulic actuator higher speed setting until normal operator action is taken to reduce the speed setting to the desired control point.

Only one of the governor actuator sections may be in control at one time; otherwise, governor instability can result.

8.1.5 Nuclear Application Governors

Diesel engines used to supply Class 1E power to electrical load at nuclear power plants require very precise control to ensure proper operation under emergency conditions. Governors specific to nuclear applications will be covered in detail below.

8.1.5.1 Types of Governors in Nuclear Service

Mechanical-Hydraulic Governing - For units equipped with only the mechanical-hydraulic governor such as the UG8, the governor functions in response to a speed sensing flyweight assembly. Changes in engine load/demand tend to cause a change in the engine’s operating speed (RPM). The flyweight assembly, in response to changes in the engine speed, increases or decreases the fuel delivery to maintain the desired speed through the hydraulic servo system.

These units are predominantly the earlier units supplied to the nuclear industry. Most of the later units use the Electric Load Sensing governing systems.

Electric Speed and Load Sensing - When the electric governor is used, both speed sensing and load sensing are provided and controlled by the electric control box through a signal in the electric section of the governor actuator. The control box senses the engine speed by either converting the generator voltage signal to a voltage proportional to the frequency or by means of a speed sensor (magnetic pickup) mounted on the engine near the flywheel or other gear that operates in proportion to the engine's speed. Load is sensed by having both the current and voltage at the generator output measured through current and potential transformers. A section within the control box converts these input signals to a voltage proportional to the real load (KW) on the generator.

When the unit is operated in parallel with the power grid, droop is introduced into the control box. The droop may be adjusted from 0 (isochronous) to about 10% by means of the "droop" potentiometer. When paralleled, some droop must be present to provide for load sharing. When the unit is run alone, the droop function may be switched off (governor switched to isochronous).

Electric Governor Backup - In most applications of the electric governor, the governor actuator mounted on the engine includes a backup mechanical-hydraulic governor. In order that this mechanical backup governor not interfere with the operation of the electric governor, it is intentionally set to operate at a speed higher than the normal speed of the unit. The lever system in the actuator forms a low pass OR gate such that the lowest speed input controls the unit. With the mechanical backup governor set high, the electric governor then controls. Should the electric governor fail, the mechanical backup governor will automatically take over control, but at the higher speed setting. It is necessary to manually adjust the backup governor to get back to the normal speed setting. If the mechanical backup governor is set at the same speed as the electric governor, the two systems could fight each other and instability would occur. The mechanical backup governor is normally set to operate at about 63 hertz in order to provide latitude for operation of the electric governor.

8.2 <u>Engine Governor Operation</u>

There are several types and models of governors used to control EDG operation in nuclear plant applications. Since they all operate on the same basic principles, we will concentrate our discussion on the Woodward series EG Governor Actuator and the EGA control box. Some more recent units have the Woodward 2301A control box and some units are now being converted to the 2301A system because of obsolescence of the EGA control box. The differences will be explained later.

It should be realized that Woodward Governor Company has obsoleted the EGA control and the Motor Operated Potentiometer speed setting units. They will no longer supply nor repair older units. Therefore, the 2301A has become the only unit now qualified for Nuclear Service. A program is underway to replace EGA controls with the 2301A control. This conversion/replacement program is discussed later in this Chapter.

8.2.1 Woodward EG Governor Actuator

The Woodward EG-B Governor Actuator, shown if Figure 8-5, is the mechanical portion of the electric governor system. The “B” in the designation indicates that the actuator includes the mechanical-hydraulic backup section/function. A number following the “B” indicates the work effort rating of the actuator in foot-pounds of torque at stall.

When the actuator is provided with the backup section, it is normally termed as a ‘reverse acting’ actuator. That is, the signal from the control to the actuator is inverse to the difference in the speed error detected by the control box. The reason for this inversion is to cause the actuator to go to the mechanical backup governor should the electrical signal from the control box disappear/fail.

The actuator consists of two separate but interconnected governors; the mechanical backup section and the electric transducer section. The mechanical-hydraulic governor section controls engine speed when the mechanical backup governor is in control (set lower than the electric governor). When the electric governor is in control (set lower than the mechanical backup governor and receiving a signal from the electric control), the mechanical section goes to the full output position so that the end of its floating lever becomes fixed.

The actuator, mounted vertically to the engine governor drive assembly, is driven directly from the engine gear train which allows it to sense engine speed. The actuator unit incorporates its own oil reservoir and pump which supplies the hydraulic pressure needed to operate the fuel control assemblies. Hydraulically, the EGB actuators consists of three distinct but interconnected sections.

Mechanical Backup Section - A mechanical-hydraulic (flyweight type) governor functions to control the engine speed when the engine is operated at speeds other than near rated speed or in the event the electric governor control has failed.

The mechanical Backup Section is the same for both the EGA system and the 2301A system.

Electric Transducer Section - The second governor is the actuator portion which works in conjunction with the Electric Control Box (EGA or 2301A control). When the actuator is used with the Electric Control Box (EGA or 2301A Control), the actual monitoring and governing takes place in the control box.

When the Electric Transducer Section is in control, the Mechanical Power Piston would be in its full upward position (fixed) and the electrical power piston is then free to move and control the input to the hydraulic amplifier.

The second section of the actuator consists of the electric transducer wherein the signal from the electric control box is used to position the electric pilot valve in that section. When there is no signal from the electric control, the electric power piston goes to its full output position, and its end of the floating lever becomes fixed. To insure this happens upon failure of the EGA electric control box signal, the center of the electric pilot valve is intentionally offset. This causes the EGA control box to put out a small signal in order to hold the electric pilot valve in the centered (blocked) position. This EGA bias voltage is usually set at between 0.5 and 1.0 volts. The full swing of the EGA electric control box signal is from -6 to +6 volts.

In the case of the 2301A system, the voltage to the actuator is proportional to the inverse of the fuel required to regulate the engine speed, and there would normally be a voltage on the transducer coil. In the event that the 2301A control box fails, the voltage would go to zero (the full output condition) and the actuator would go to the mechanical backup section control.

Hydraulic Amplifier Section - The third section is the hydraulic amplifier section which provides the output force needed to operate the fuel controls on the engine. Again, the Hydraulic Amplifier Section is the same for both the EGA system and the 2301A system.

The three sections are connected through a loading piston which functions to position the terminal output shaft of the actuator in response to changes in either of the first two sections.

The hydraulic amplifier section, shown in Figure 8-5, consists of an oil sump, oil pump, accumulator assembly (pressure storage and regulation), relay valve assembly, relay piston and linkage to the terminal shaft.

The governor drive shaft causes rotation of the oil pump and the relay valve bushing. Rotation of the pump gears draws a suction on the oil reservoir, and the oil is discharged to the accumulator section.

The accumulator provides a reservoir of oil under pressure while also acting as a pressure relief/regulating valve. Oil pressure from the pumps acts against the force of the accumulator springs. As the pistons pass the bypass port, excess oil pressure is vented back to the sump. Normal oil flow continues on to the top side of the relay servo piston and on to the relay valve plunger and bushing. The relay servo piston connects to and controls the piston of the terminal output shaft of the actuator.

The relay valve plunger, which is controlled by the loading piston, controls oil flow to the underside of the relay servo valve. When the engine is operating in a steady state condition, the control land of the relay valve plunger just blocks the port to the underside of the relay servo piston. This creates a hydraulic lock which prevent oil pressure, acting against the top of the relay servo piston, from forcing the piston downward.

When there is a change in engine speed or generator load, the loading piston will move as a result of the action of the mechanical-hydraulic or electric governor, depending on which is in control. This movement of the loading piston causes the relay valve plunger to raise or lower.

When there is an increase in generator load or a decrease in engine speed, the loading piston will rise. This will, through the linkage shown, cause the relay valve plunger to drop, directing oil pressure to the underside of the relay servo piston. Since the bottom of the relay servo piston has a larger area than the top, the larger force of the oil acting on the bottom of the piston will cause it to move upward. This upward movement is carried through the terminal shaft to the fuel control linkage causing the fuel delivery to the engine to increase.

During a decrease in generator load or increase in engine speed, the loading piston is forced down, raising the relay valve plunger and relieving oil pressure from the underside of the relay servo piston. The reduced pressure on the underside of the relay servo piston causes a net downward force on the piston. The piston is forced down, reducing fuel delivery to the engine.

The relay beam, intermediate shaft, and bearing transfer the movement of the relay servo piston back to the relay plunger valve. This returns the relay plunger valve to the blocking or steady state position.

8.2.1.2 Electric Governor Section - EGA

The electric governor section controls the position of the loading piston (as shown in Figure 8-5A) and ultimately the relay servo piston and terminal output shaft by controlling the movement of the electric governor power piston.

The control element of the electric governor section is the pilot valve plunger which is attached to an armature magnet. A centering spring suspends the armature magnet and pilot valve in a transducer and magnet. The transducer and magnet is electrically connected to the EGA control box. A signal from the control box causes the armature magnet and pilot valve plunger to move up or down in response to changes in the generator speed/load.

With the unit operating at a steady state condition, a small signal is present in the transducer and magnet. As such, the pilot valve and plunger are centered, blocking the port and creating a hydraulic lock below the electric governor power piston. A change in the generator load or speed causes the signal to be change by the EGA control box, which will move the pilot valve plunger up or down.

An increase in load or decrease in speed on the generator will result in a signal from the EGA control box causing the armature to move down. This motion allows oil to be directed to the underside of the electric power piston. The increased pressure on the underside of the power piston will cause it to rise, raising the loading piston. This action, as discussed earlier, results in the relay valve plunger directing oil to the underside of the relay servo piston, which causes the terminal shaft to move the fuel control assemblies (racks) to the increased fuel position required to re-establish rated speed.

With a decrease in load or increase in speed of the generator, the EGA control box will provide a signal to the transducer and magnet causing the pilot valve plunger to move up. This upward motion of the pilot valve plunger vents oil from the underside of the electric governor power piston. As the electric governor power piston moves down, it causes the loading piston to move down, which raises the relay valve plunger. Upward movement of the relay valve plunger vents oil from the underside of the relay servo piston causing it to move down. This downward movement rotates the terminal output shaft to the reduced fuel position required to re-establish rated speed.

Operational stability is achieved by a negative feedback to the compensating land of the pilot valve plunger through the buffer system. Oil from the governor oil pump is directed to the top of the compensating land of the pilot valve plunger and to the left side of the buffer piston. The right side of the buffer piston is connected to the underside of the compensating land of the pilot valve plunger. This pressure creates sufficient force to move the pilot valve plunger up, returning it to the steady state blocking condition. Movement of the power piston ceases, and the engine accepts the increased load on the generator. The sensitivity of the buffer system is determined by the setting of the needle valve, which functions as an orifice between the two sides of the buffer piston and compensating land.

8.2.1.3 Mechanical-Hydraulic Governor

Figure 8-5 shows the mechanical-hydraulic governor section, combined with the electric governor and the amplifier sections. The mechanical-hydraulic governor section functions only when the electric governor control box is not functioning or when the mechanical speed setting is below the electric control speed setting. When the mechanical-hydraulic governor is in use, the electric governor section is hydraulically locked with the electric governor power piston fully extended (fixed). The mechanical-hydraulic governor setting is normally slightly higher than the speed setting used for the electric governor to prevent the two sections from acting against each other.

The pilot valve plunger of the mechanical-hydraulic governor is connected to the flyweight assembly. This section also includes a buffer system consisting of a buffer piston, needle valve, and compensation land as was used with the electric governor. The desired engine speed (RPM) is established by setting the force applied by the speeder spring which acts to oppose the motion of the flyweight assembly.

With the engine operating at the desired speed, the centrifugal force acting on the fly-weights exactly balances the force applied by the speeder spring. This equilibrium condition holds the pilot valve plunger in the blocking position, locking the mechanical governor power piston and the loading piston in the steady state condition.

Should the mechanical load on the engine increase, the engine tends to slow down. This reduces the centrifugal force of the flyweights acting against the speeder spring of the valve. The force of the speeder spring overcomes the centrifugal force and the pilot valve plunger lowers. Oil pressure is then applied to the of the buffer piston moving it to the right. This displaces the oil on the right of the buffer piston, applying its pressure to the underside of the mechanical governor power piston. The power piston moves upward, repositioning the loading piston, thereby increasing the fuel delivery to the engine.

The pressure differential created is also applied, via the needle valve, to the compensating land of the pilot plunger. This moves the pilot valve plunger upward. At the same time, the upward movement of the mechanical governor power piston acts to move the speed adjusting/speed droop floating lever upward, reducing the force applied by the speeder spring on the flyweight assembly. This allows the pilot valve plunger to return to the steady state blocking position.

8.2.1.4 Actuator Dial Settings

The mechanical linkage, as shown on the left side of Figure 8-5, is connected to the three adjustment knobs on the face of the governor (see Figure 8-4). These adjustment knobs allow for setting specific operating parameters for the mechanical-hydraulic section of the governor.

The "**Speed Setting**" knob is connected to the speed adjust lever through a screw shaft and clutch. This allows the operator to manually set the desired no-load engine speed by adjusting the force of the speeder spring. In the nuclear application, this knob is normally set at the '**high speed stop'** position.

The **"Speed Droop"** knob only effects to speed droop of the mechanical backup governor section of the Actuator. Electrical Droop is set in the Control Box.

The term "Speed Droop" refers to the difference in engine speed between no-load and full load operation. It is a key factor when operating two or more units in parallel or when operating connected to an infinite bus (electrical grid). For example, if the unit were connected to a grid without speed droop, that unit would attempt to lead the entire grid. This would lead to unstable operation and possible damage to the generator and/or engine. See the discussion earlier on the definition and use of speed droop.

Operationally, speed droop is a function of the position of the mechanical-hydraulic power piston. Movement of the power piston causes a proportional movement of the speed adjusting/ speed droop floating lever which reduces the force on the speeder spring on the flyweight assembly. Setting of the Speed Droop knob moves the adjusting pin (fulcrum point) which changes the lever ratio between the mechanical governor power piston and the speeder spring.

With the speed droop set at 0%, the full-load speed and the no-load speed would be the same. This condition, called isochronous, is satisfactory when the unit is powering its own isolated bus. A speed droop of about 3 to 5% would be appropriate for units connected to the grid for surveillance or post-maintenance testing.

In the nuclear application, this function is not used as the system in under control of the electric governor. To ensure proper operation of the electric governor, it is recommended that the mechanical speed droop knob be set at '**zero**'.

The "**Load Limit**" knob connect through a load limit lever to the pivot lever. The pivot lever limits the upward travel of the intermediate lever regardless of the position of the loading piston and output nut. The intermediate lever, working through the bearing and relay beam, establishes the maximum fuel position of the relay servo piston and the terminal shaft. When classified as operable, the load limit knob on a nuclear application EDG would be set at the “max fuel” position. It should be noted that the ‘Load Limit” is always active, whether the unit is on the mechanical-hydraulic governor or the electric governor. It does not limit just the operation of the mechanical-hydraulic governor section. In the nuclear application, this knob is normally set at '**Max Fuel**' position.

8.2.2 EGA Control Box

The EGA Box, as pictured in Figure 8-6, is an the electrical part of an electro-mechanical servo system programmed to maintain a preset engine speed and load sharing level in proportion to the capacity of the unit being controlled. For the purpose of study, we will consider the EGA as having three sections, as illustrated in the block diagram shown in Figure 8-8 - EGA Control Block Diagram.

8.2.2.1 Input Section

The input section consists of a load sensor (watts transducer), a resistor box, a speed sensor, and a power supply section. During operation, the speed sensor receives a signal from one phase of the generator output via potential transformers and converts it to a DC voltage proportional to the speed of the engine. This voltage is then fed into the amplifier portion of the circuit at the summing junction. This is called the speed transducer.

The Load sensor receives voltage and current signals from each of the three phases of the generator output and uses these signals to calculate the total electrical (KW) output of the generator. This calculated total load is converted to a DC voltage through a bridge of rectifiers and is fed into the summing junction if the system is set up for droop or load sharing operation. This section includes a potentiometer that allows this watts transducer to be calibrated to the specific unit rating, etc. Another potentiometer allows the amount of droop desired to be set into the system if the unit is in the droop mode of operation.

Another input is from a potentiometer or another electrical/electronic device that sets the level of the load or speed at which the unit is to run. This is called the speed reference.

8.2.2.2 Control Section

The control section consists of a set of differential amplifiers and power amplifiers. An input signal is fed into these from the summing junction.

The speed reference section supplies a regulated DC voltage to the speed setting potentiometer (which is mounted outside the EGA Control Box). The output of this potentiometer is adjustable by the operator or by automatic control, and the output (proportional to the desired speed) is also put into the summing junction. The voltages from the speed setting potentiometer and the speed transducer (mentioned above) are the same value but they are of opposite polarity so that the resulting voltage at the summing junction is zero when the engine is at the desired speed.

The droop switch controls the load sensor output in both the droop and isochronous modes. In the isochronous mode, the output of the load sensors is fed to the summing junction only if the unit is set up for isochronous load sharing with other units on the same isolated bus. In the droop mode, however, the output of the load sensor is fed to the droop control and then into the summing junction. The droop control is used to adjust the percent droop (1 to 10%) by applying a variable portion of the load sensor output to the summing junction.

The summing junction calculates the algebraic sum of the input signals from the load sensor, the speed sensor, and the speed setting potentiometer. This summed signal becomes the input signal to the amplifier section.

Operational stability is achieved by regulating the rate of change of the actuator from one level to another during load or speed changes. This dampens out transients and oscillations in the control of the engine.

8.2.2.3 EGA Output to Actuator

The output of the EGA Control Box is fed to the actuator. The magnitude and polarity of the signal determines the movement of the armature and pilot valve plunger.

During steady state conditions, the armature is centered in the transducer and magnet. With only the bias voltage applied to the coils, the pilot valve plunger takes the neutral or blocking position.

Under conditions of increasing load, the output signal for the amplifier is applied to the coils of the transducer and magnet. The polarity of the signal causes the armature to move downward, increasing the fuel delivery to the engine. When the engine reaches the desired operating conditions, the signal ceases and the pilot valve plunger returns to the steady state position.

With a decrease in load or increase in engine speed, the polarity of the signal is reversed. The armature now moves upward, allowing the oil pressure under the electric power piston to return to the sump. This lowers the loading piston, leading to a reduction in fuel delivery to the engine.

8.3 The 2301A Governing System

The 2301A Governing System is of slightly more recent development. With the obsolescence of the EGA system, it is the best logical replacement for the EGA system. See the comments in the section below on the conversion of the EGA system to the 2301A system.

8.3.1 2301A Actuator

The actuator used with the 2301A control system looks identical to the EGA actuator on the outside except for the nameplate. The actuator type number ends with the letter 'C' for compensated and with a the letter 'P' for proportional actuator. The differences inside are not great. The mechanical-hydraulic section is identical as is the amplifier section. The only difference is in the electric section. The 2301A compensated actuator does not have the buffer section and the needle valve because the compensation is all done electronically in the control box. For the proportional actuator, the transducer has a system of levers that feed the electric power piston position back to the transducer to bias it in a position between its centering springs that are proportional to power output.

On the actuators with backup sections, the transducer and 2301A are set up for reverse action operation. That is, the voltage to the actuator is low for increased fuel and higher for idle or no fuel.

In all other respects and settings, the 2301A actuator is the same as the EGA actuator. The same dials and settings are used.

8.3.2 2301A Control Box

The 2301A control box is shown in Figures 8-7 and 8-9. This control has the same basic connections as the EGA control. It has load sensor connections from the generator terminals through potential and current transformers so that the KW load on the unit can be measured. This is used primarily to set the droop mode as the voltage connections are not used for the governor power supply or for sensing the unit speed. Figure 8-10 shows the external connections to be made to the 2301A control box.

It is necessary to provide power to operate the governor, and this can be either from a DC supply at 20 to 40 volts, or an AC or DC supply at 88 to 132 volts for AC input, or 90 to 145 volts for a DC supply. For Nuclear EDG, the input voltage it typically 125VDC.

Like the EGA, there are terminals for the signal going to the actuator. There are also terminals for input of the speed reference signal, either from a motor operated potentiometer (like the EGA control) or from a Digital Reference Unit (DRU) or other voltage reference signal.

Unlike the EGA, the 2301A requires a speed signal supplied from a Magnetic Pickup (MPU). This pickup is usually mounted next to a gear (such as the flywheel or coupling ring) with a speed input proportional to the engine's speed. Figure 8-11 shows a typical Magnetic Pick (MPU) unit. This is an assembly of a fine coil of wire wound over a permanent magnet, housed within a magnetic material body. Any metallic (particularly magnetic) material that passes by the tip of the pick will influence the magnetic field and cause the MPU to put out a pulse. It is used to count the teeth of a gear to establish the speed of the engine.

Like the EGA, the 2301A can be used in isochronous mode or in droop mode. In the case of the 2301A, only one switch contact is necessary to control the operating mode.

8.3.3 Speed Reference Input

The speed reference (the speed at which the operator wants the unit to run) can be input from a number of sources. To make the system as flexible as possible, including changing speed setting rapidly and automatically, the Digital Reference Unit (DRU) is preferred. Figure 8-14 shows the DRU unit and its inputs and connections are shown on Figure 8-15.

The DRU allows one to set an idle speed, a maximum speed, and set point speed. The set point speed would normally be the rated speed of the unit. The operator can also raise and lower the speed for manual control of the speed during engine maintenance or for loading the unit once synchronized to the offsite power system.

The DRU has two possible ramp rates such that on one ramp rate, the rate of changing the speed can be slow so that operators feel comfortable when making speed or load adjustments. By closing a contact, a fast ramp rate can be selected for use in getting the unit up to rated speed rapidly in the event a “start” signal is received while the unit is at idle or some other intermediate speed condition. On units converted to date, much flexibility is evident as systems have been developed to meet different operation/plant desires for control.

Some earlier 2301A applications used the same Motor Operated Potentiometer that the EGA system used. With the obsolescence of the MOPs, the DRU also becomes a viable replacement for the MOP on both the earlier 2301A systems and on the EGA systems.

Figure 8-12 shows a typical 125VDC Motor Operated Potentiometer, with its internal circuitry shown in Figure 8-13.

8.4 Governor System Change Out

The EGA governor system components, particularly the EGA control box, have become obsolete. Some of the electronic components are no longer available, and using new components would require a wholesale redesign of EGA circuit boards.

Woodward Governor Company has stated that they will no longer supply the EGA Control Box, nor will they attempt to repair older units. They have also obsoleted the MOP, as the only source of the variable resistors (potentiometers) previously used is to buy them from foreign sources.

In addition, the EGA governor requires output power from the EDG generator to operate. It will not function to control the engine. The mechanical governor must be adjusted down to the desired speed. This makes the EDG unit inoperable since it cannot respond to an accident signal to establish rated speed and voltage. For these reasons, many owners are replacing the EGA with the 2301A governing system.

The 2301A governor control receives its speed input from a magnetic pickup mounted near the flywheel or other gear that runs in proportion to the engine’s speed. Therefore, the 2301A system can control the engine speed at other than rated speed conditions.

In conjunction with the use of a Digital Reference Unit (DRU - in place of the Motor Operated Potentiometer previously supplied with the EGA system), the unit can be set up to run at a lower speed (idle at 300 rpm, for instance), and yet it can respond to an emergency signal and be at rated speed within 10 seconds.

8.4.1 Advantages and Disadvantages

The EGA did have some advantages but also disadvantages compared to the 2301A, and vise versa, as listed below.

EGA Advantages:
- Powered from Generator Voltage - self sufficient

EGA Disadvantages:
- No governing until Generator is at voltage
  - for Power Supply
  - for Speed Sensing
- Will not operate at reduced speed
- Part of compensation is hydraulic within the actuator, subject to oil temperature and condition

2301A Advantages:
- Control at all conditions (not dependent on generator voltage)
- In conjunction with DRU, can respond to emergency signal while shutdown or at idle.
- All compensation is electronic - tuned for best performance.
- Can control at idle or rated speed equally well

2301 Disadvantages:
- Requires external power supply to operate (125VDC)
- Requires Magnetic Pickup (MPU) for speed input (MPU's are very reliable)
- Requires gear wheel on engine/ generator.

Most failures, on either system, result in operation on backup governor at a higher speed.

8.4.2 Fast Start Problem

A ten-second start sequence is equivalent to 35 to 50 hours of engine operation at rated load. Fast starts ultimately reduce the life and reliability of the unit. Fast stars along with fast loading of the generator stress the engine and the generator.

The NRC authorized plants to make slow starts by Generic Letter 84-15. However, units with the EGA governing system cannot make a slow start on the electric governor. It is necessary to use the mechanical back-up governor (on the actuator). In this state, the unit CANNOT respond to an emergency start signal. The unit is effectively 'inoperable' when on the mechanical governor.

The 2301A governor, when applied with the DRU, can be operated at idle speed under electronic governor control and CAN immediately go to rated speed (within 5 seconds) upon receipt of an emergency signal.

8.4.3 Governor Conversions:

The following plants have made governor conversions:

Detroit Edison - 4 OP units
Beaver Valley - 2 PC units
Snupps-Callaway - 2 PC units
Snupps-Wolf Creek - 2 PC units
PSNH - Seabrook - 2 PC units
Calvert Cliffs - 3 OP units
VC Summer - 2 PC units
Duane Arnold - 1 of 2 OP units (Nov)

The following other plants are contemplating governor conversions:

Alabama-Farley - 2 OP amd 3 PC units
Millstone III - 2 PC units
PECO-Limerick & Peach Bottom – OP's
Indian Point - 3 ALCO units.

8.5 Other Possible Governor Systems

Over the last few years, governor suppliers have developed a number of other types of governing equipment. Most of these involve digitizing the governor control algorithms used. One such governor system provided by Woodward Governor Company would be the 2301D, a digital version of the 2301A (an analog system).

Another is the 700 series, specifically the 723PLUS units. There are a number of reasons that these particular units are not appropriate for use in nuclear power plant applications. These governor packages have many, many features that make them ideal for specific application requirements that are not appropriate for nuclear plants.

Both the 2301D and the 723 series can be provided with dual dynamics that allow the same governor, by closure of switch/relay contacts, to operate a diesel fuel burning unit or a gaseous fueled or dual fuel unit to be managed equally well. The gas engines must have a much slower responding governor in that mode in order to keep the air to fuel ratio under tight control. Such is not applicable to straight diesel engines in nuclear service.

Another problem with using these units in nuclear service is that their power supplies are limited to 18 to 40VDC, while most nuclear plant station battery power systems are at 125VDC. To apply these units to nuclear service would require that either one of the following be provided:

- A separate battery power supply, or
- An inverter type power supply, to decrease the voltage for the power to these governors. This type of power supply generally introduces reliability problems, and their output can be noisy and affect governor stability.

A voltage reducing scheme could be used, but with the 125VDC power supply having to operate between 90 and 140VDC, there is a problem with stability in that type of supply - they are hard to regulate when both the input voltage and the load current can change that drastically.

For generator applications, the 723 series comes in two parts – the 723 unit to control the speed and the DSLC (Digital Synchronizer and Load Control) unit for input of the generator parameters in order to have the system operating in the droop mode for surveillance testing. Or, the 723 unit would need a GLC (Generator Loading Control) in order to simulate a load control signal. The combination of these units requires much more space in the generator control panel than the 2301A or the 2301D. The 723 series would not be applicable as a retrofit for the obsoleted EGA system (whereas the 2301A or D will generally fit in the space vacated by the EGA components).

Nuclear power plant governor applications are really quite simple: to provide good stability and the ability to respond rapidly to sudden and large load changes (such as starting large pump motors) and to provide a means of controlling the loading on the unit during monthly surveillance testing. The 2301A can operate just as well for these simple tasks as the more sophisticated digital units. The primary limitation for large load pickup is not the governor, which always acts fast enough, but the engine itself. (Refer to the discussion at the end of Chapter 10.)

8.6 Governor-Linkage Relationship

Regardless of the type of governor used, there has to be a relationship between the governor output and the fuel injection system components–the fuel racks. This is normally provided by some sort of linkage consisting of levers and links. Most governors used in nuclear plant EDGs have a rotary output, referred to as a 'terminal shaft.' Some may have a linear output and require a 'J' bar linkage system. Figure 8-16 shows the relationship normally set up between a governor with a rotary output (45 degrees of rotation typical of the EGB actuator) and the engine fuel requirements.

On this diagram, note that the linkage relationship established certain key conditions to allow for engine operation under a number of conditions as described below. When the governor is at the minimum (no) fuel position, the engine must also be at the 'no fuel' condition; otherwise, the governor may not be able to shut the engine down. In fact, the governor is usually set up such that there is a slightly negative fuel rack position when the governor is at minimum fuel just to ensure that the governor can shut down the engine. Many governors contain a shutdown solenoid that when operated, puts the governor terminal shaft at minimum fuel in order to shut down the engine from a remote location.

The engine requires some fuel to operate when it is idling. The typical position is as shown on the diagram. The engine also has to occasionally run at an overload. Therefore, the linkage must ensure that the governor can move the fuel racks to at least that position plus some margin. The full/rated load position is somewhat less than the overload position as shown. Typically, the governor linkage is set up to use about 60 to 70% of the governor travel in getting the engine from idle to full rated fuel as shown.

8.7 Engine Overspeed Governor/Trip

Mechanically, diesel engines must operate within a specific speed (RPM) range. In order to maintain the proper frequency, EDGs have a set RPM which is maintained by the engine control governor. Should the governor fail to maintain the proper engine speed or should there be a failure in the fuel injection system which prevents control of the engine, the engine could increase in speed to an unsafe level.

Such overspeed conditions, which could result in severe engine and/or generator damage and fire hazards to operating personnel, are not uncommon with diesel engines. To prevent such a condition, a redundant speed monitoring or overspeed device is required.

The overspeed device may be a separate governor driven by the engine gear train, or it may be a separate overspeed trip mechanism such as that shown in Figure 8-17.

The overspeed trip shown in Figure 8-15 is mounted directly to the end of the engine camshaft. Since camshaft speed is either equal to or one half the engine crankshaft speed, this is an ideal location for such a device. The trip shaft and trip pawl are mounted directly to the engine while the flyweight and spring assembly rotate with the engine camshaft.

During normal operation, the force of the spring is sufficient to keep the flyweight clear of the trip pawl. During an overspeed condition, the centrifugal force acting on the flyweight is sufficient to overcome the force of the spring. This allows the flyweight to move outward. The flyweight makes contact with the trip pawl, unlatching it from the trip shaft. The trip shaft, which is spring loaded, rotates as shown to activate the trip mechanisms, which by its spring force, returns all of the injectors to the no-fuel position. With no fuel going to the engine cylinders, the engine coasts to a stop. If the engine is still loaded, it stops rapidly. With this system, fuel to the engine is shutoff in less than one engine revolution.

An engine overspeeding is one of the two conditions that are allowed to shut the engine down. Overspeed trips are normally set to activate at 110 to 115% of the engine's rated speed. The overspeed trip or overspeed governor normally is required to be reset manually. The engine overspeed is active under all engine operating conditions and modes.

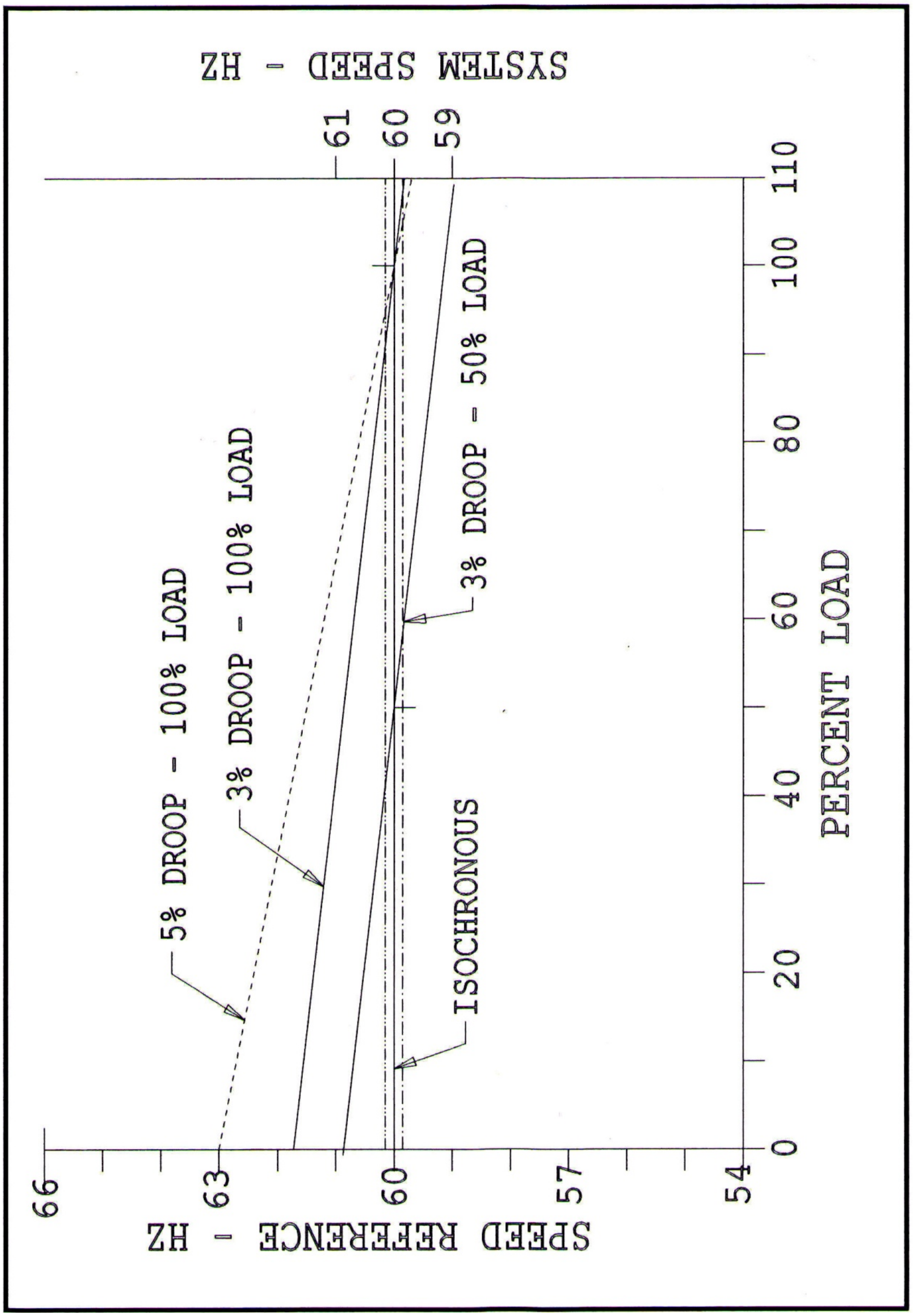


Figure 8-1 Droop-Isochronous Relationship

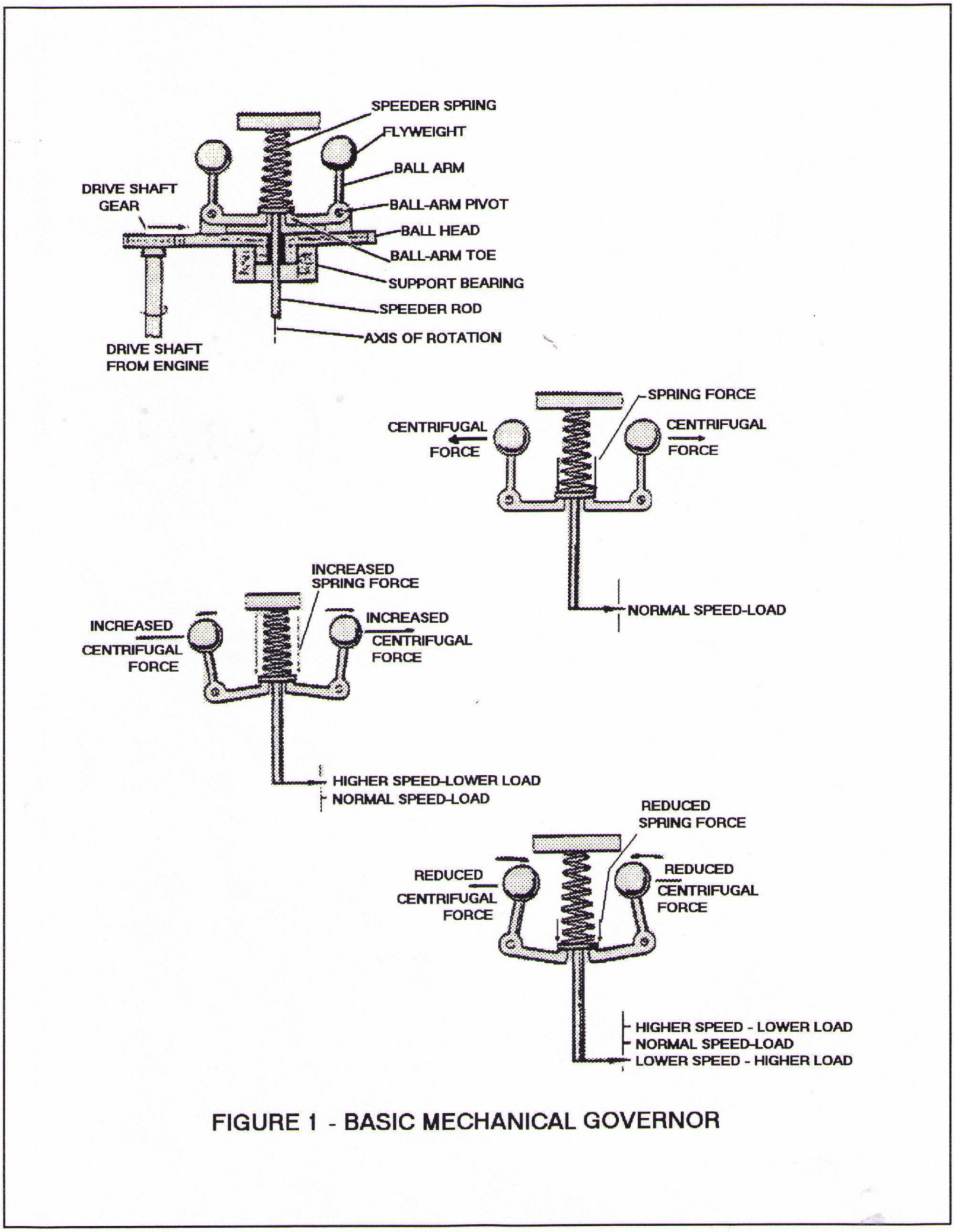


Figure 8-2 Basic Mechanical Governor

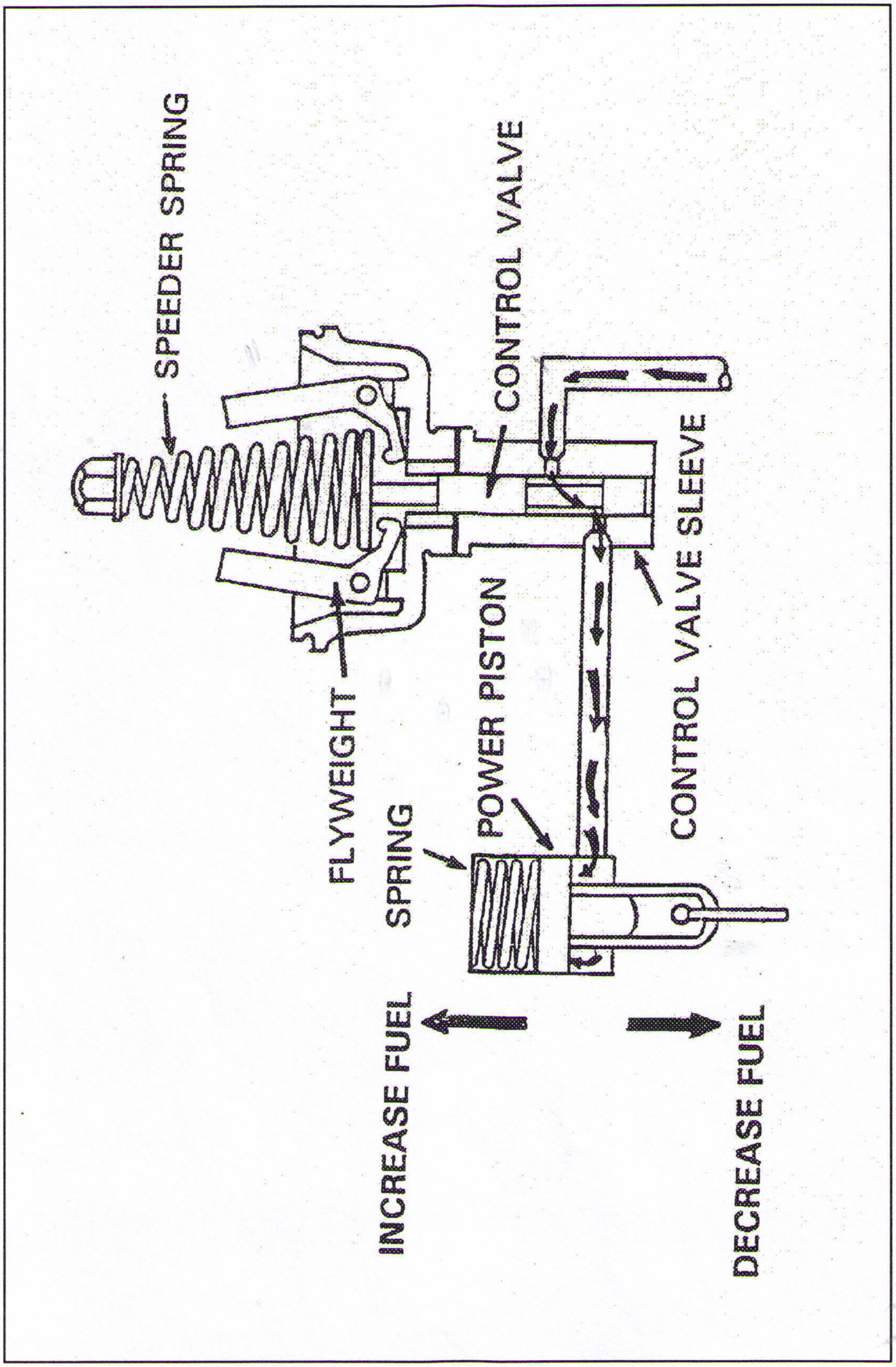


Figure 8-3 Basic Governor with Hydraulic Power Piston

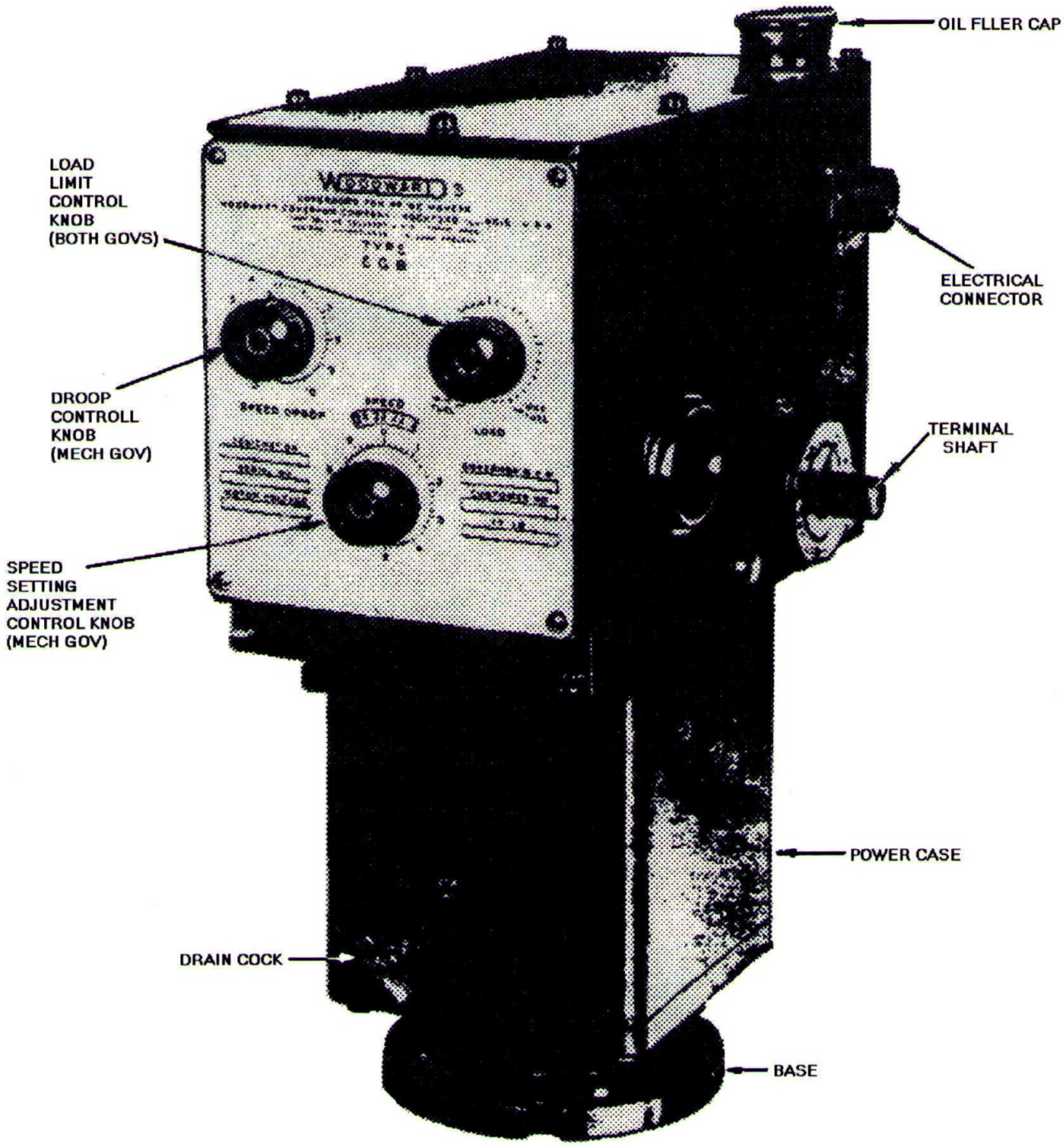


FIGURE 4 - HYDRAULIC ACTUATOR

Figure 8-4 Electronic Governor Hydraulic Actuator

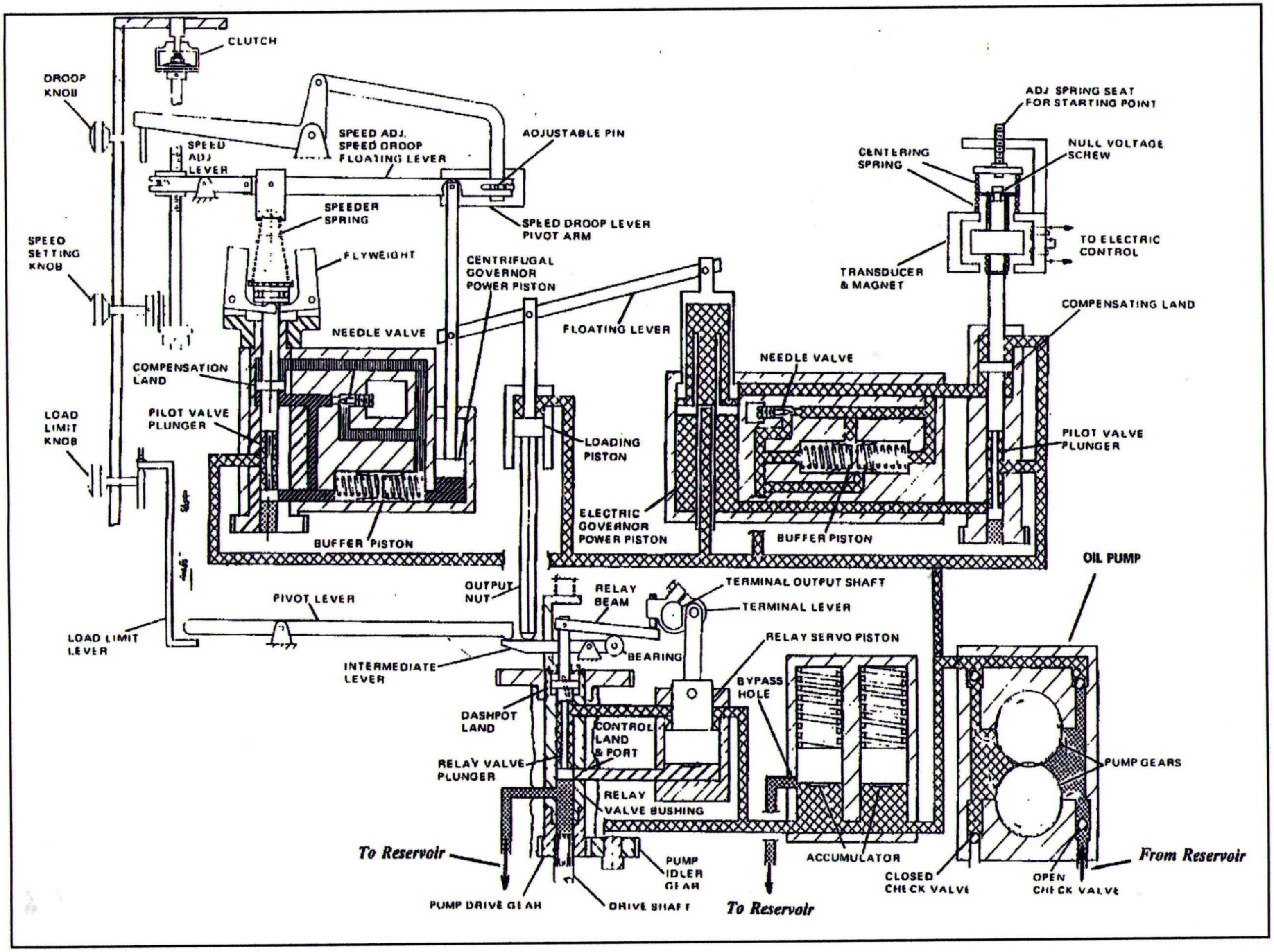
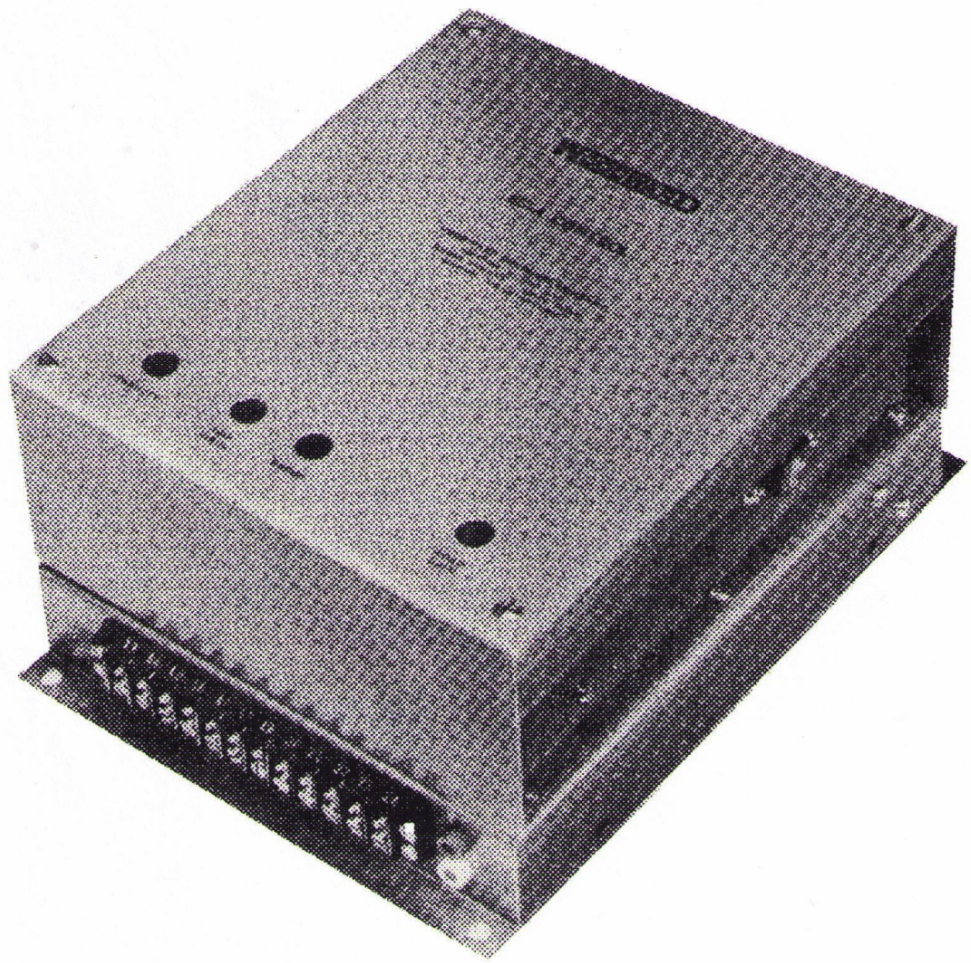


Figure 8-5 EGB-10C Actuator Schematic



EGA CONTROL BOX

Figure 8-6 EGA Governor Control Box

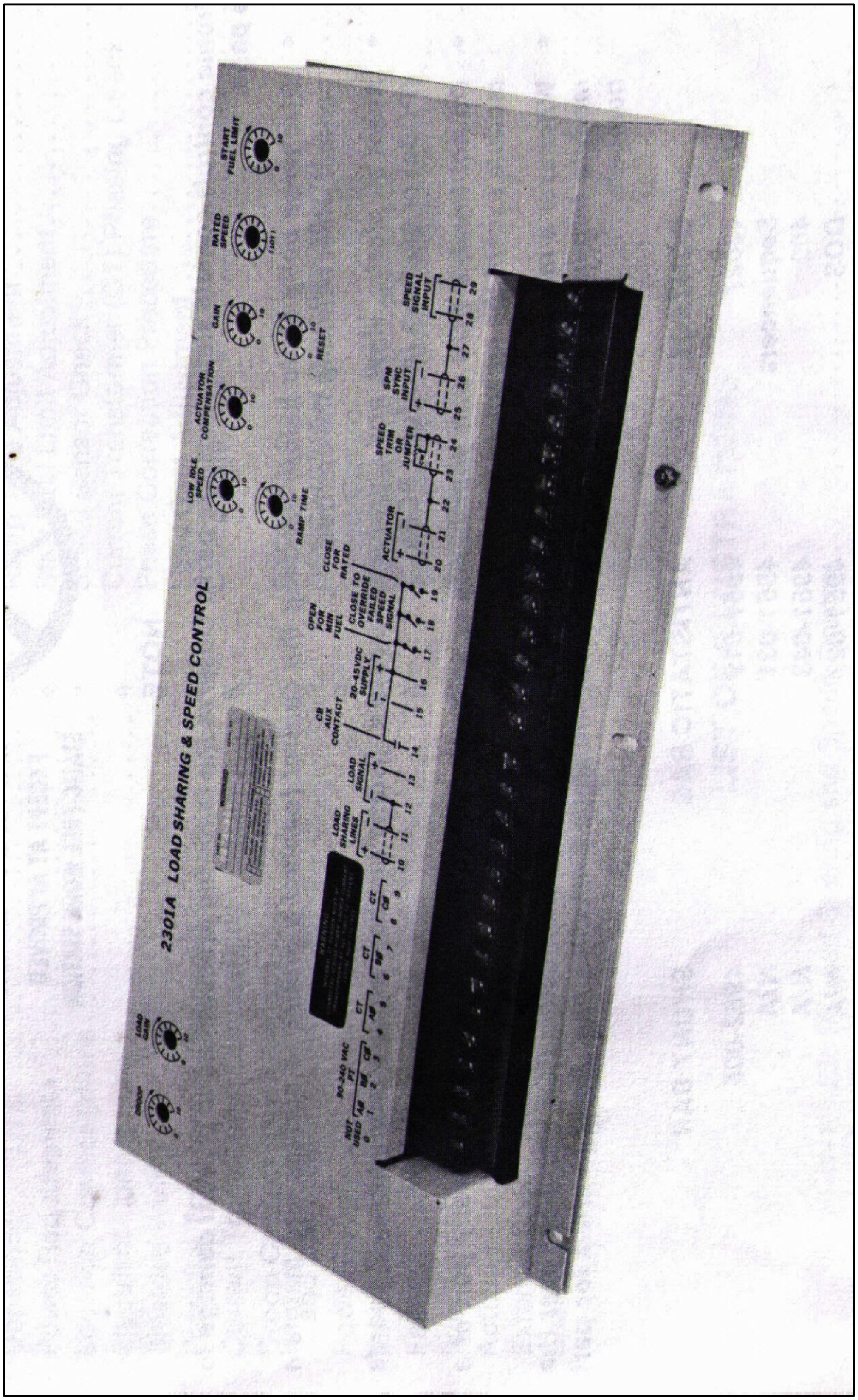


Figure 8-7 2310A Control Panel

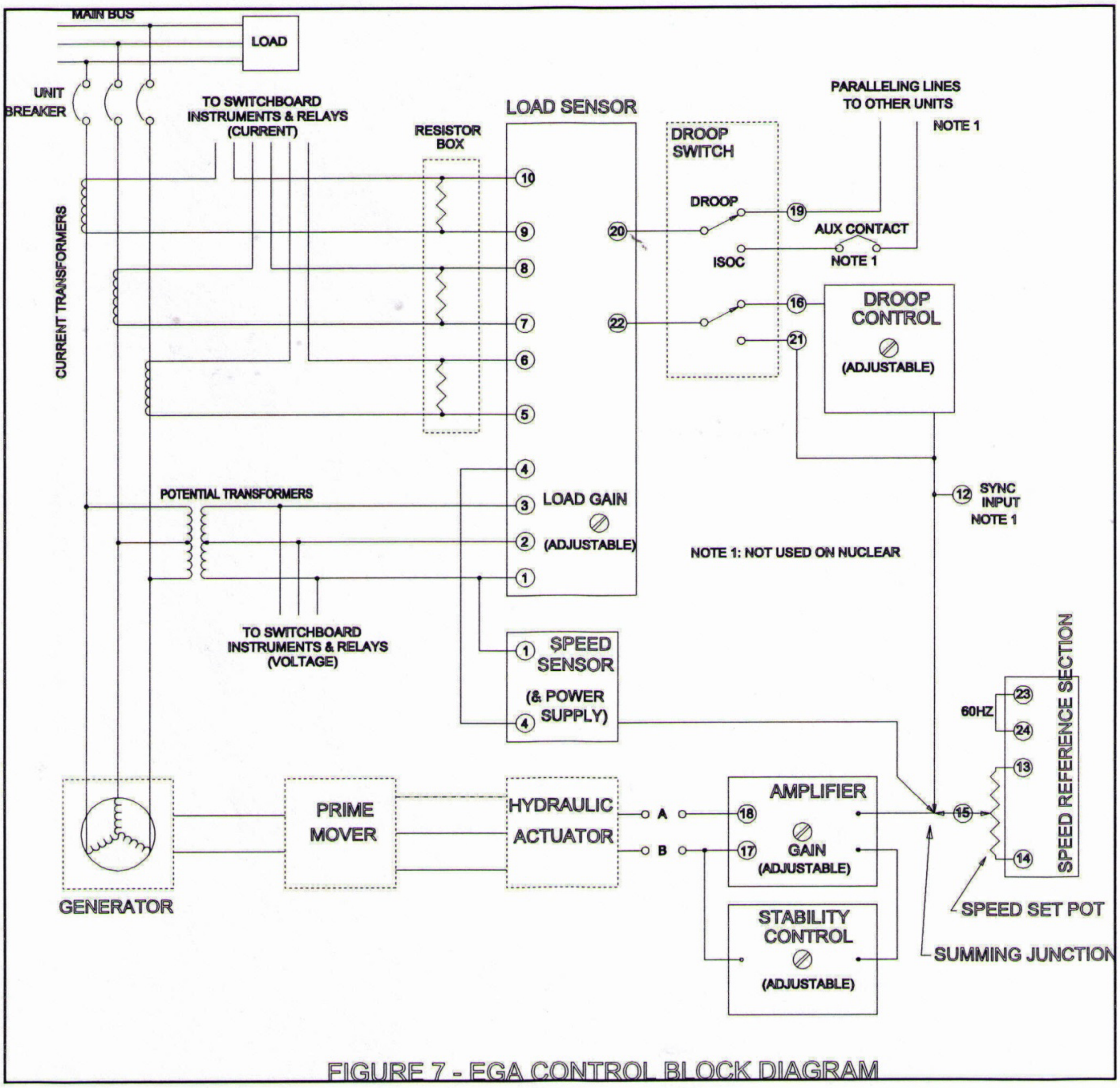


Figure 8-8 EGA Control Block Diagram

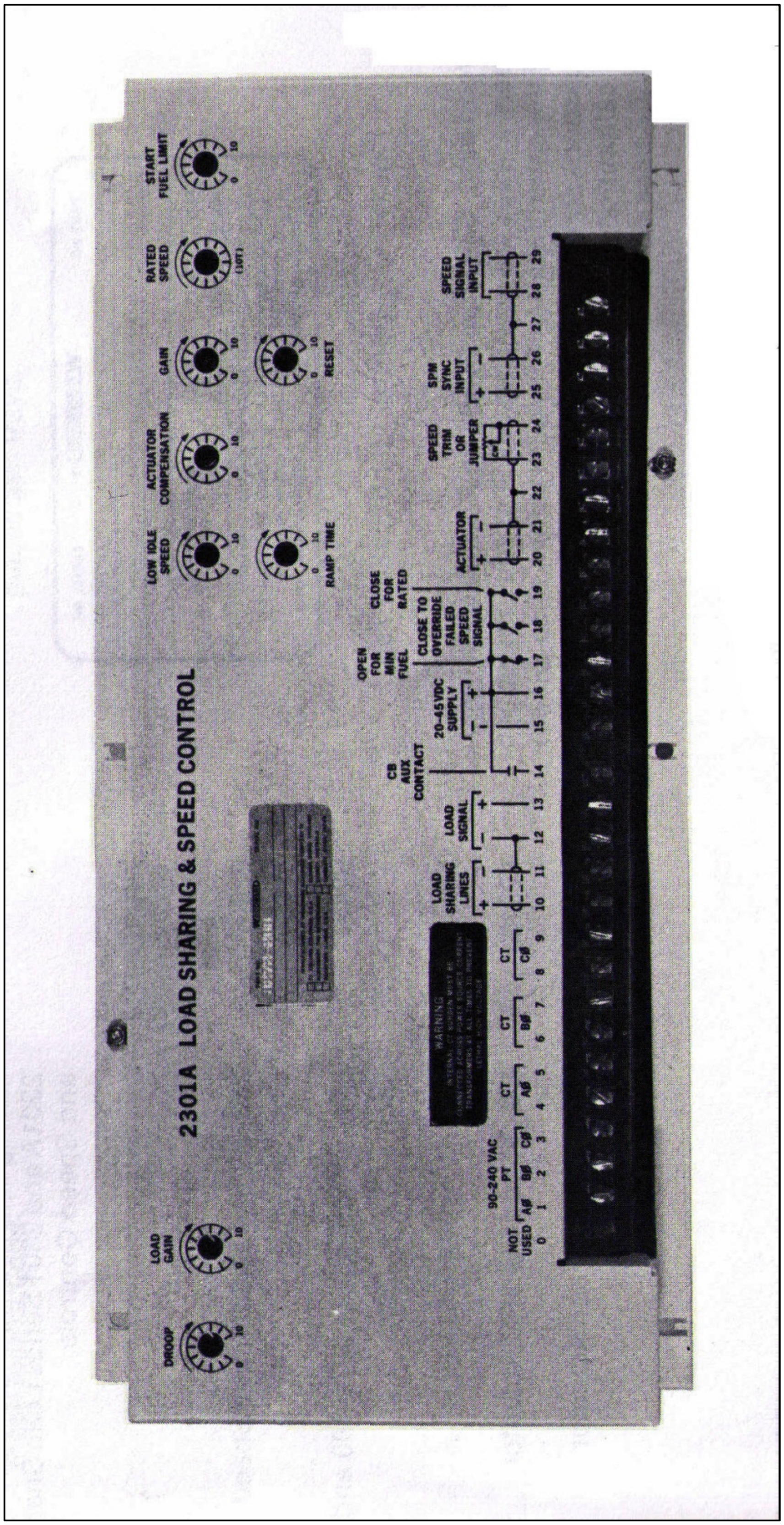


Figure 8-9 2391A Governor Control Box

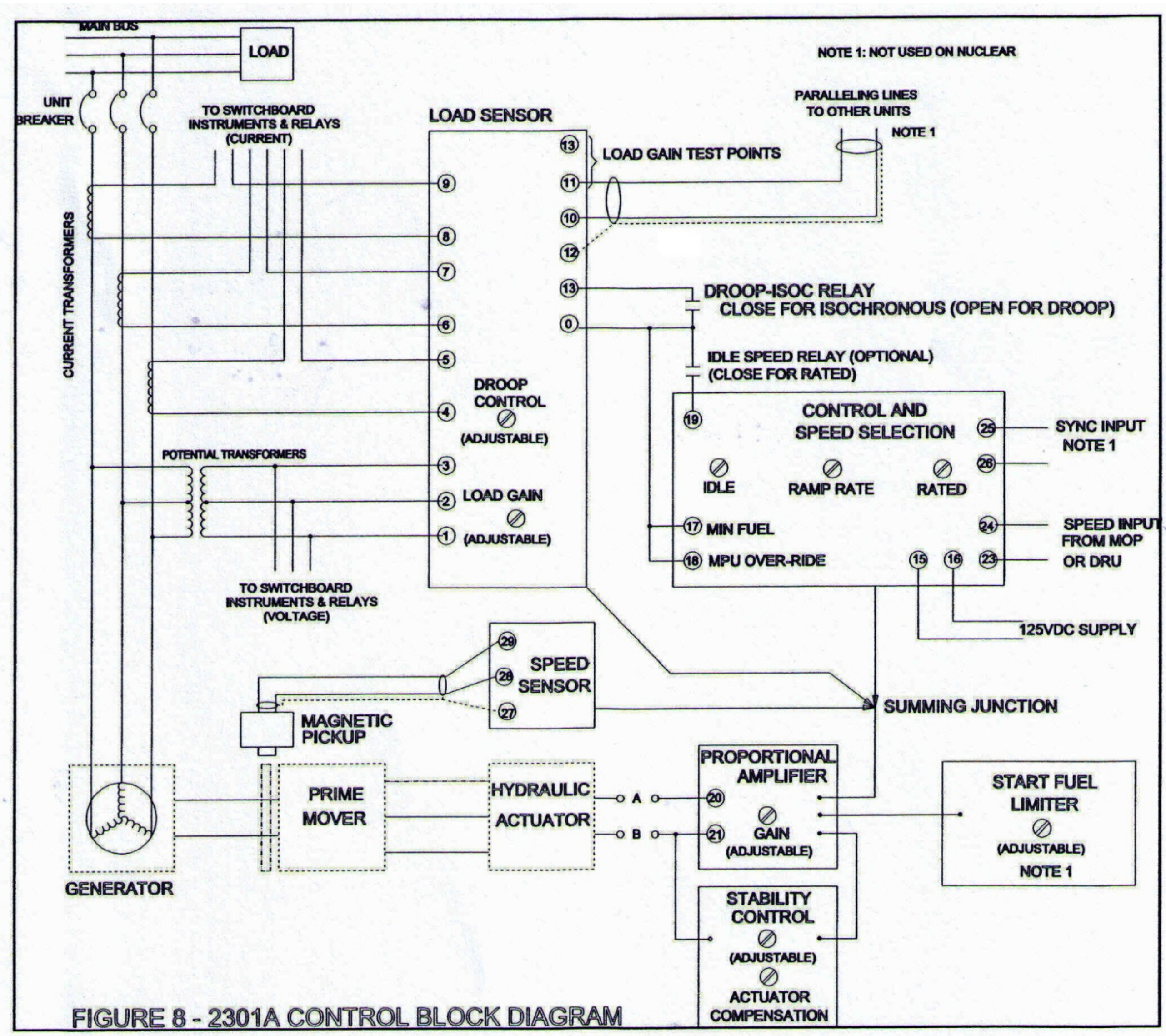


Figure 8-10 2301A Control Block Diagram

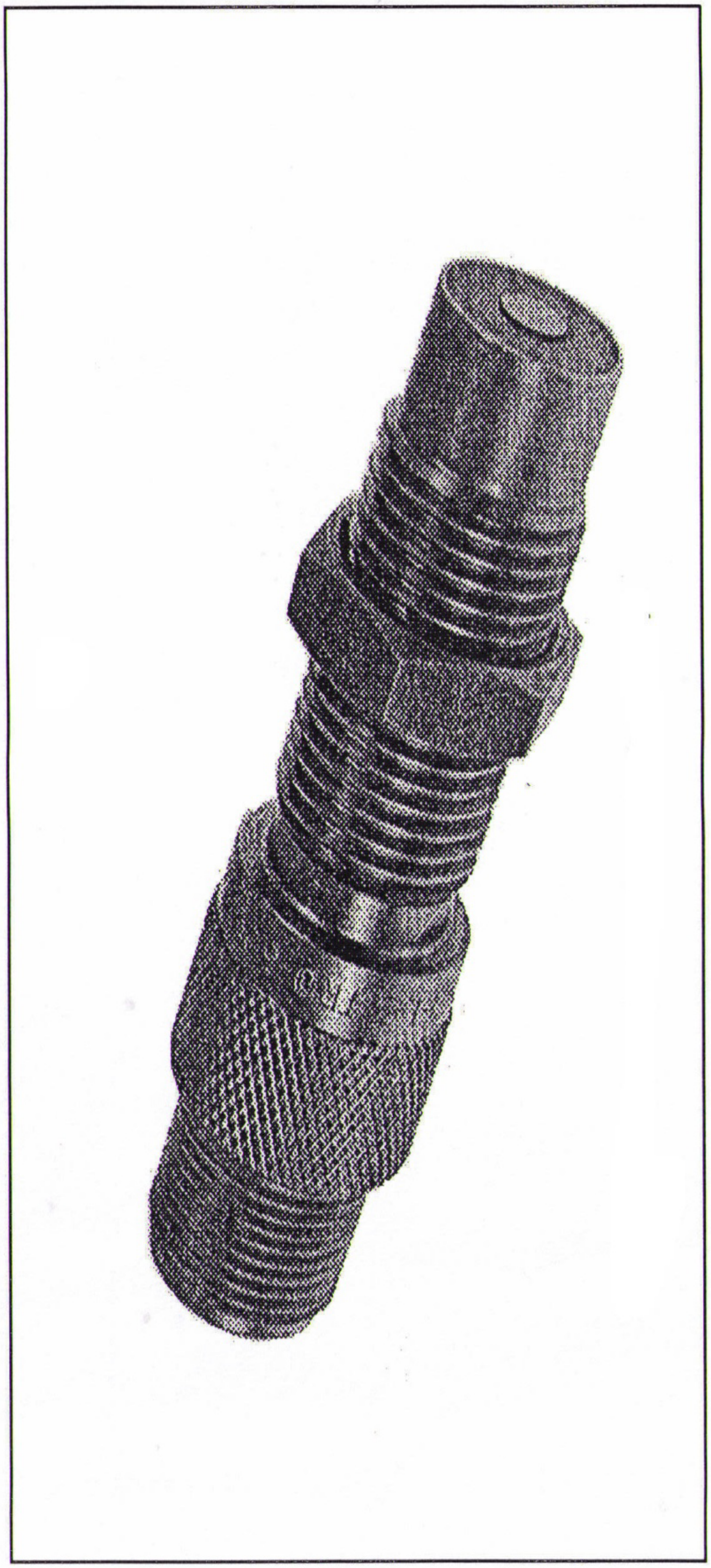
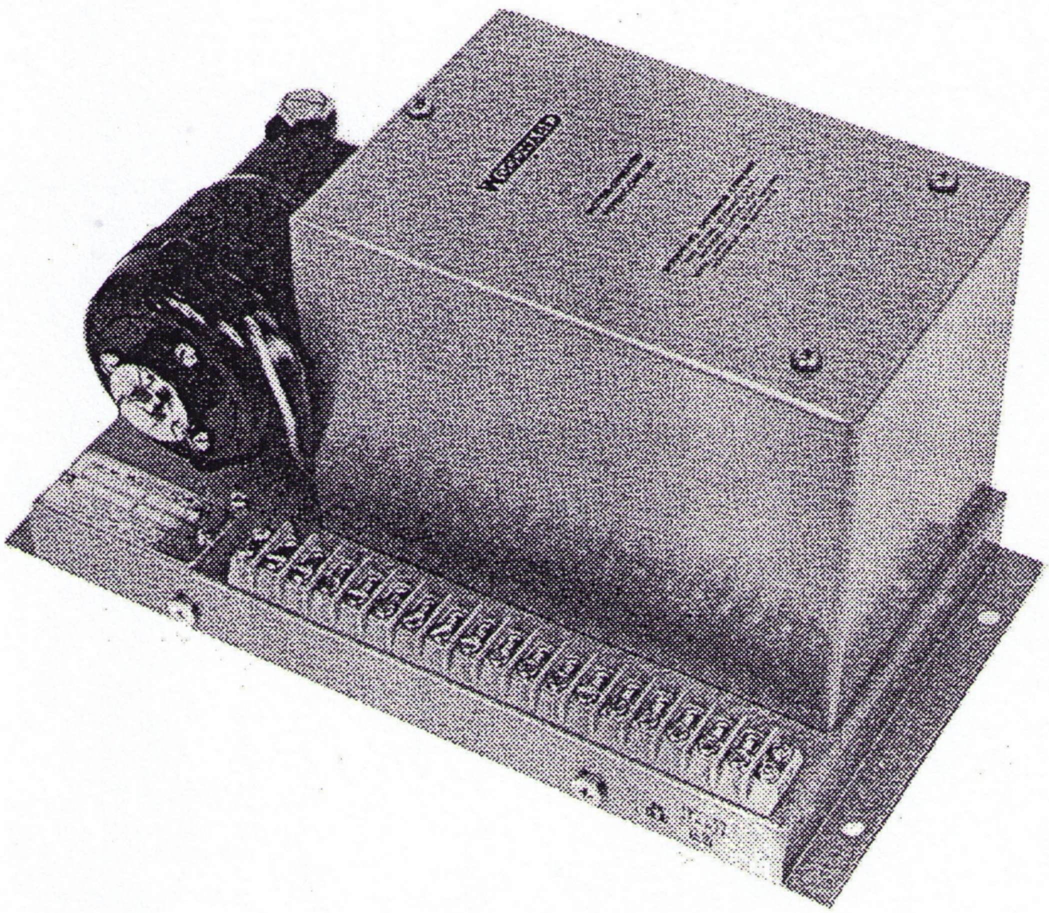


Figure 8-11 Typical Magnet Pickup



MOP FOR 125VDC MOTOR

Figure 8-12 MOP for 125VDC Motor

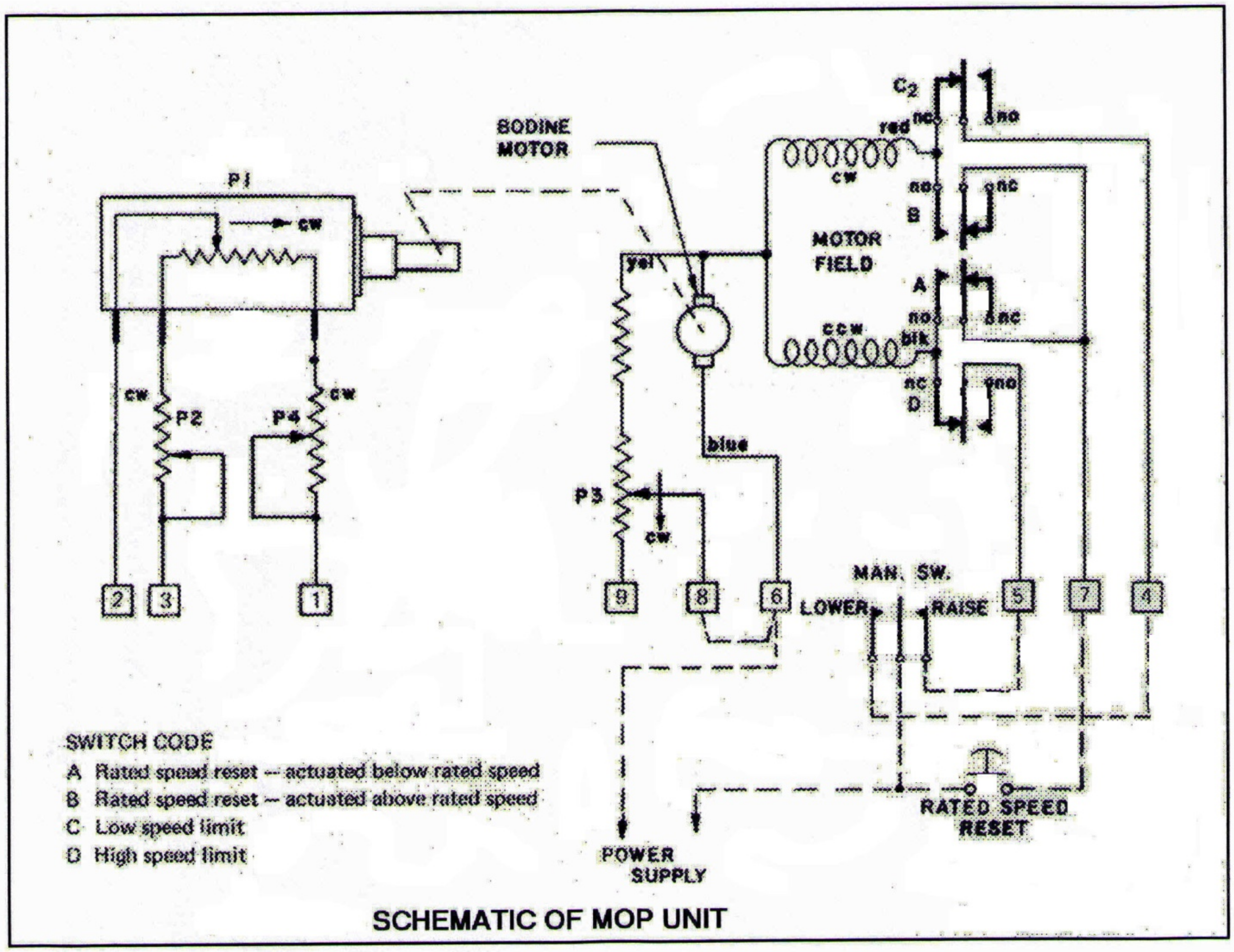
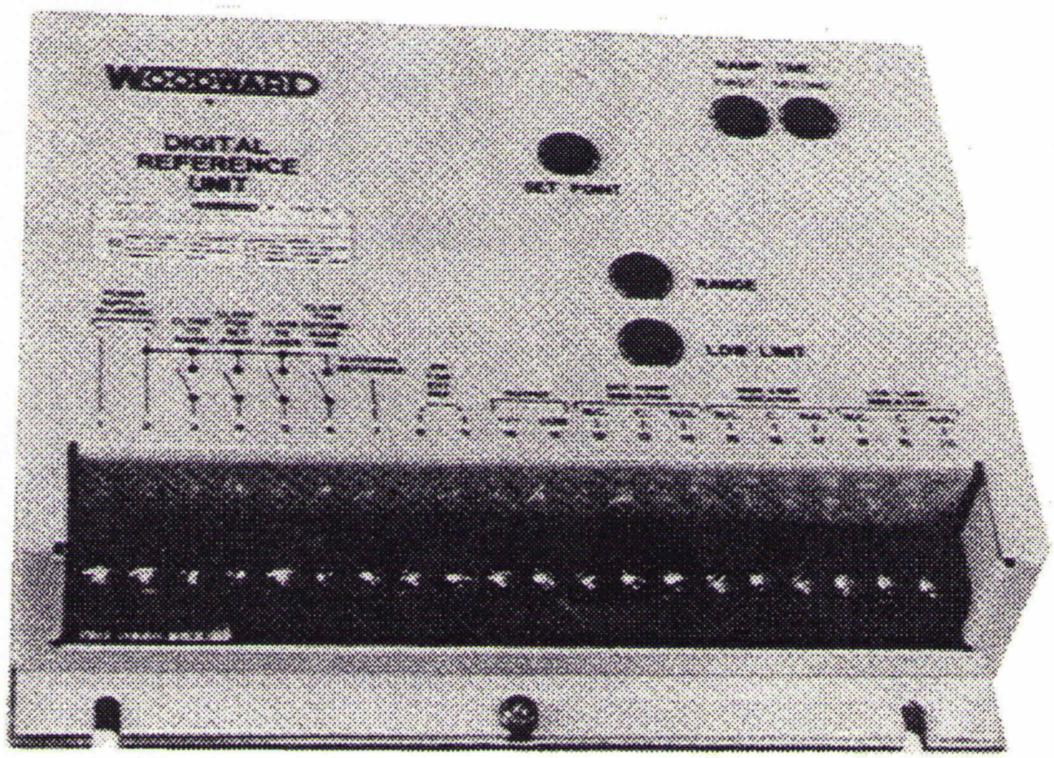


Figure 8-13 Schematic of MOP Unit



DIGITAL REFERENCE UNIT (DRU)

Figure 8-14 Digital Reference Unit (DRU)

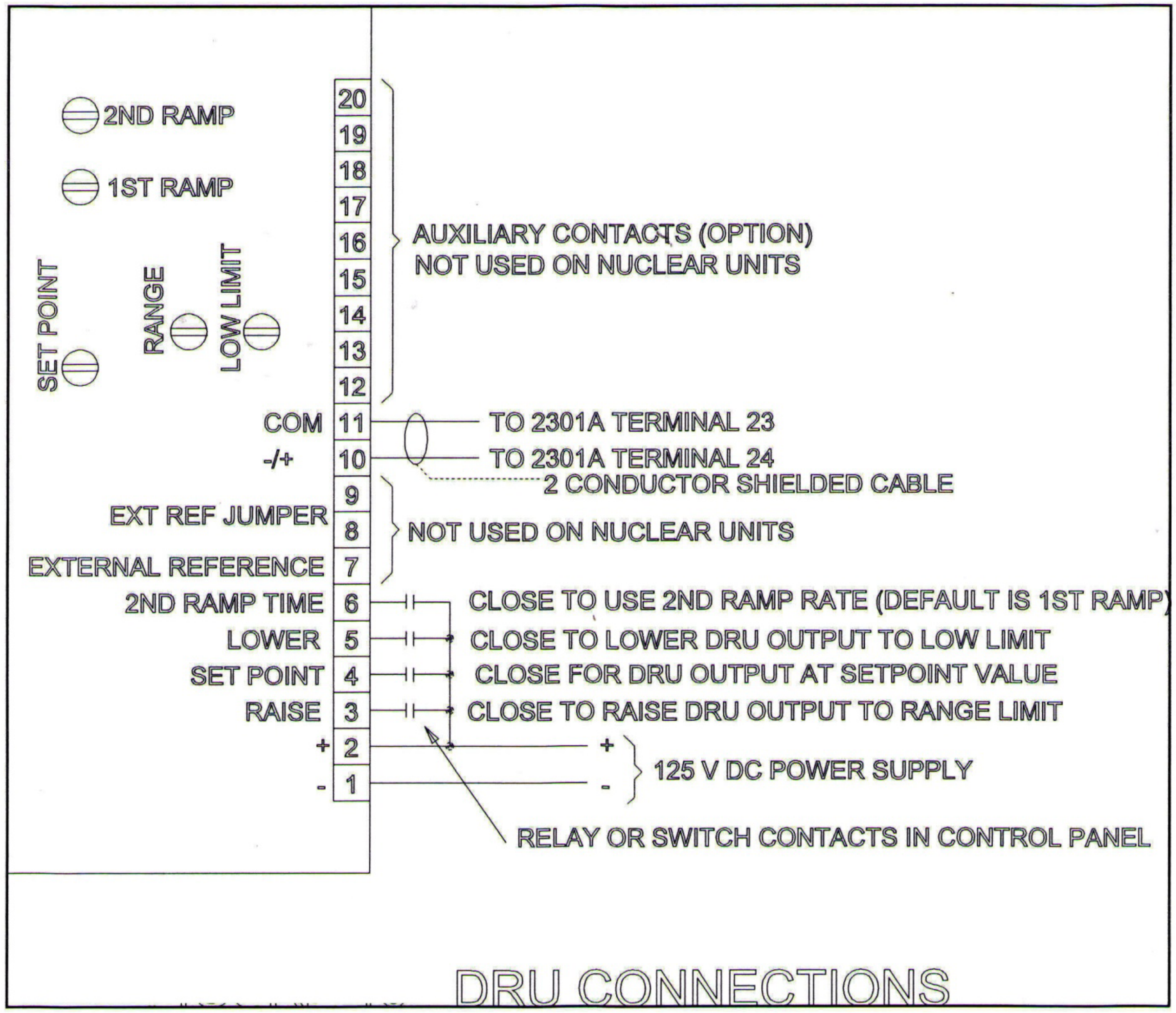


Figure 8-15 DRU Connections

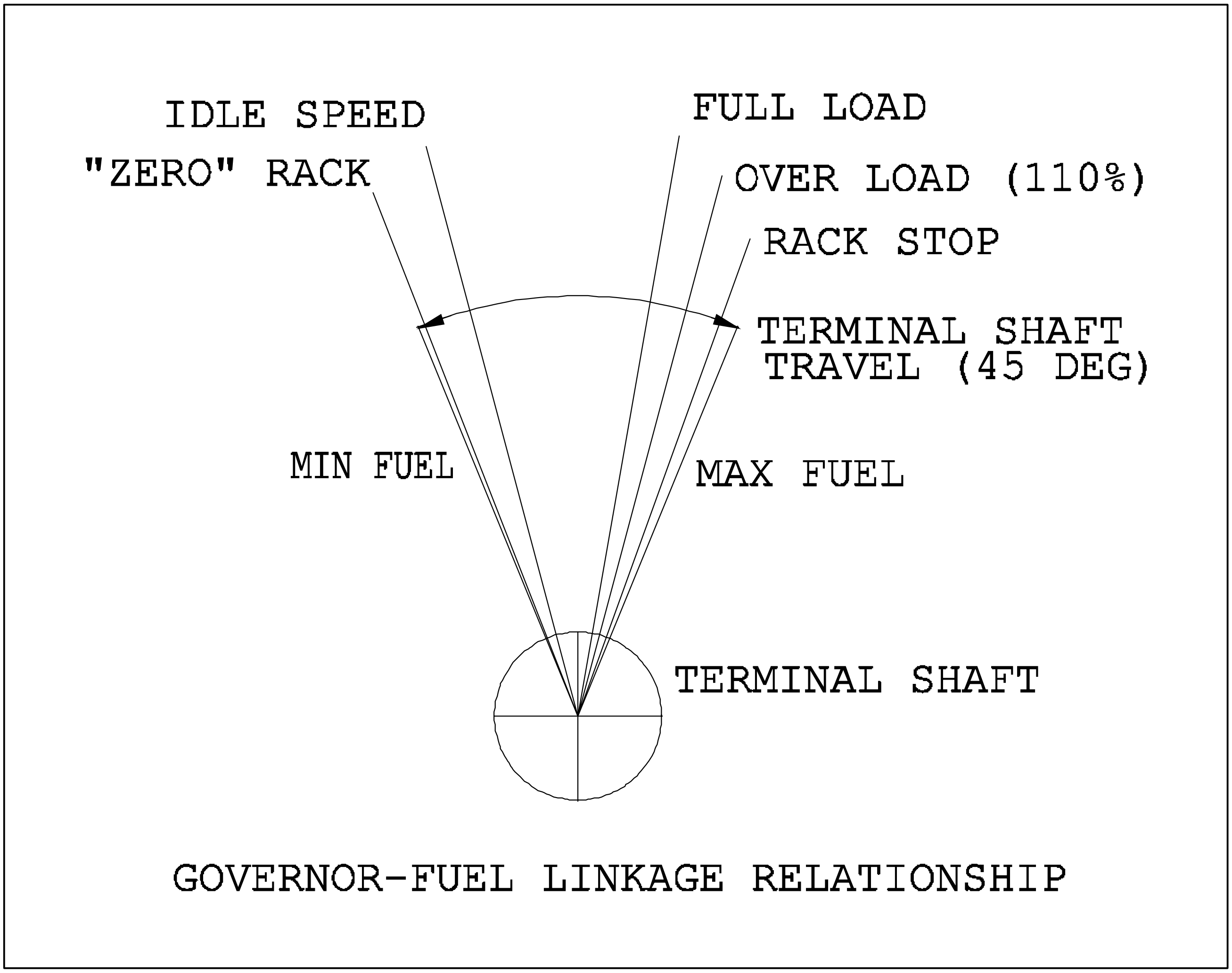


Figure 8-16 Relationship Between Governor Output & Fuel Control (Rack)

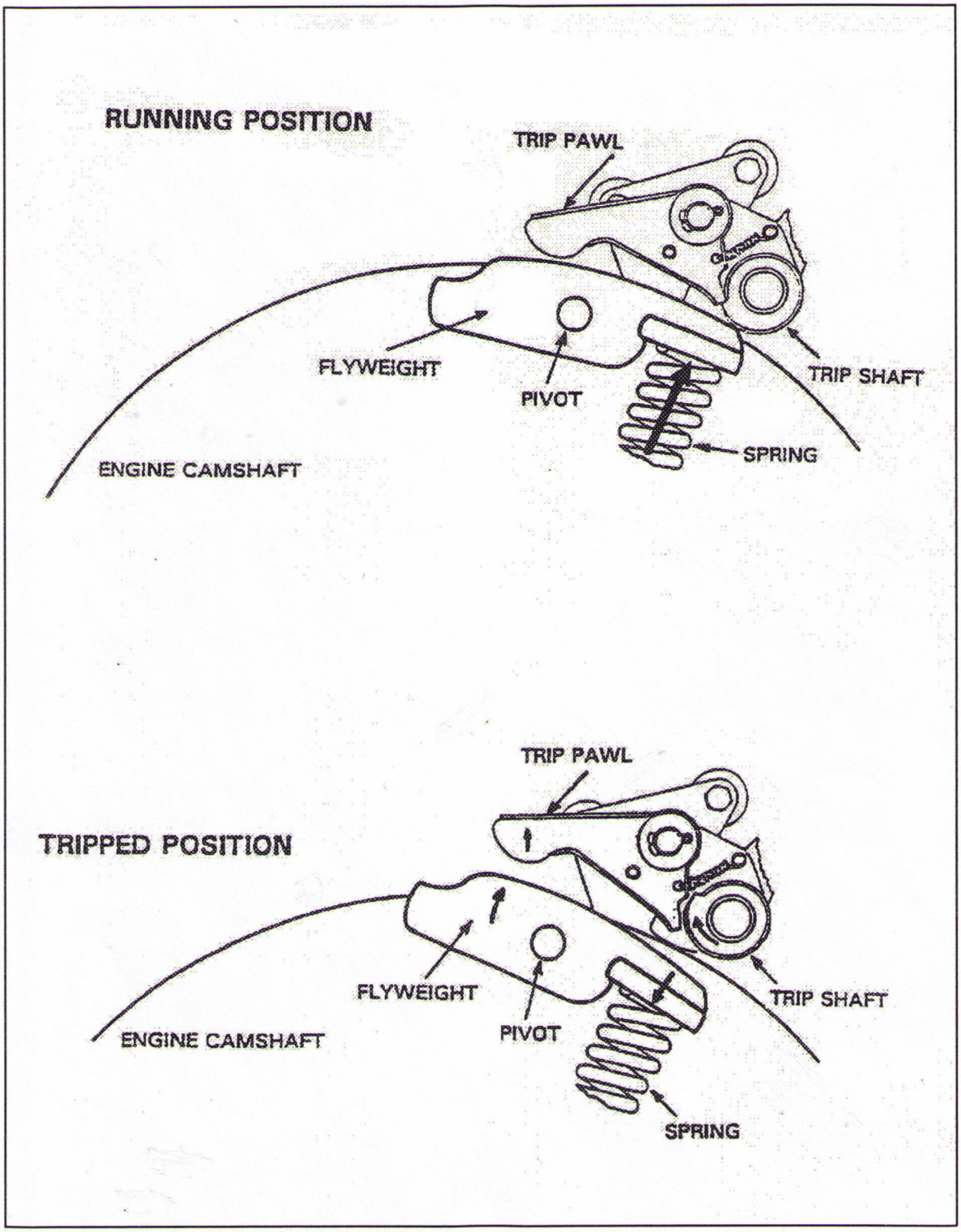


Figure 8-17 Overspeed Trip (Governor) Mechanism