SECTION 5. LC-LOOP CONTROLLER
PC-700/900 Programmable Controllers

5-1. GENERAL DESCRIPTION

The Loop Controller (LC) function implements user-defined, closed-loop process control systems. (See paragraph 5-22 for a description of the LC function.) Closed-loop systems, in general, are characterized by an ability to compare the actual value of some process variable with its desired value and to take the necessary corrective action.

Regardless of the method (type of controller) used to control the process, all closed-loop systems share the same basic block diagram. (See Fig. 5-1).

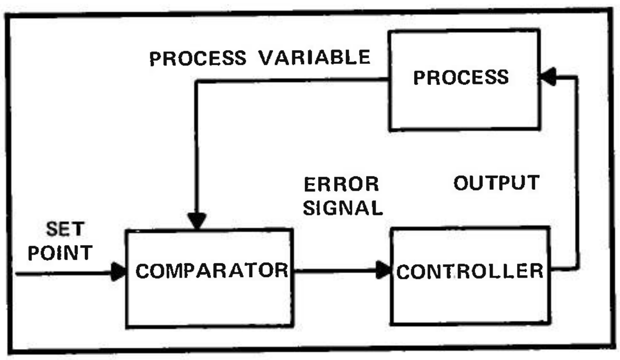


Figure 5-1. Closed-Loop System

Consider the manual closed-loop system shown in Figure 5-2.

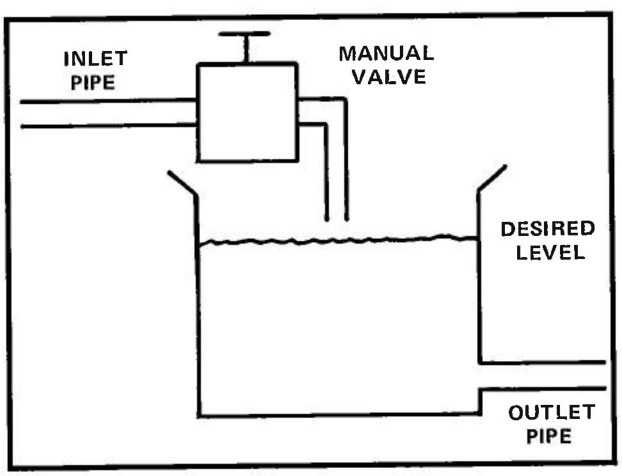


Figure 5-2. Manual Closed-Loop System

As shown, this system operates in an open-loop fashion (i.e., the process variable, liquid level, is not actively compared to the desired level, and no spontaneous corrective action is taken to maintain the desired level). This system could become closed-loop in operation by adding an operator. The operator closes the loop by fulfilling the roles of the comparator and the controller. The operator sees that the actual height is not the desired height, and adjusts the flow from the inlet pipe to keep the liquid level at its desired height. However, this is a very inefficient method of control in a rapidly changing environment. This same system could be automated, as shown in Figure 5-3.

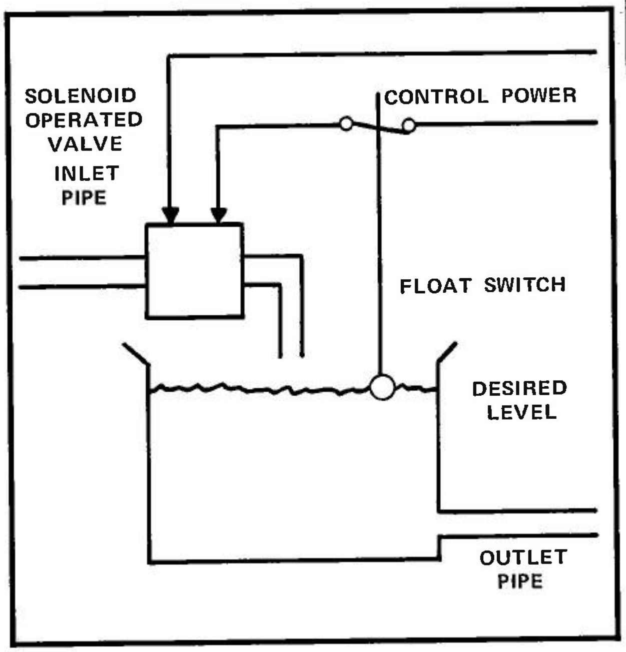


Figure 5-3. Simple Closed-Loop System

As shown, the simple closed-loop system operates to keep the liquid level at the desired point by turning the inlet valve ON whenever the float switch closes, and turning the valve OFF when the float switch opens. This type of system is efficient only as long as the process variable, liquid level, does not vary rapidly and/or the desired height of the liquid level does not change. Rapid variations in the level will cause frequent operation of the solenoid valve and float switch, leading to early failure and frequent replacement of these components. The desired height of the liquid level can only be changed by modifying the physical position of the float switch (possibly a time-consuming and expensive operation).

A better system is shown in Figure 5-4. It is more sophisticated, but it is also more efficient.

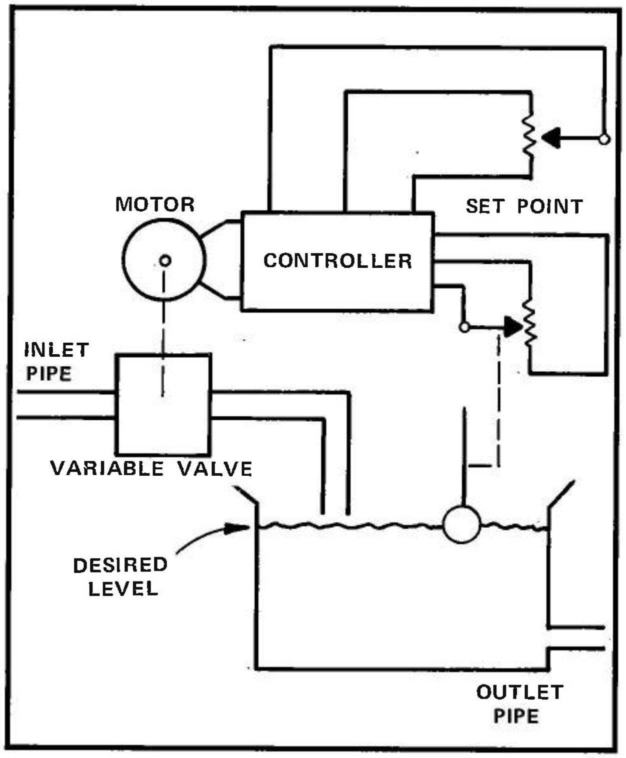


Figure 5-4. Better Closed-Loop System

As shown in Figure 5-4, the better closed-loop system operates to maintain the desired level by adjusting the input to correct for any variations without a great deal of oscillation. The set point can be easily modified by changing a setting, rather than readjusting the float switch. The valve responds to the appropriate error size (e.g., a small error results in a small flow change; a large error results in a large flow change). The actual versus desired level is closely tracked by the system.

The closed-loop system general block diagram of Figure 5-1 can be made more specific, as shown in Figure 5-5.

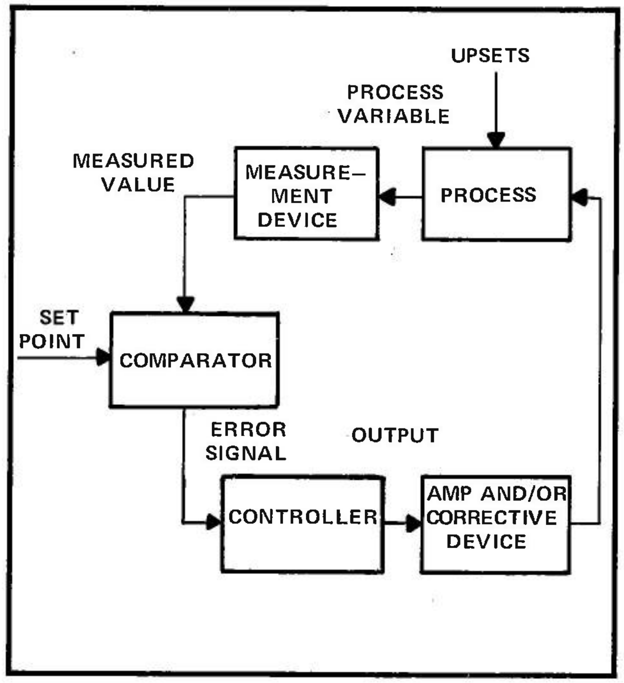


Figure 5-5. Detailed Closed-Loop System Block Diagram

Generally, closed-loop systems operate as follows: when the system is operating in a stable fashion, the set point minus measured value results in a zero error signal and a zero response from the controller; this further results in no changes to the process and no change in the process variable or measured value. In essence, the system is operating as desired. When the process changes (e.g., increased flow requirement from the outlet pipe), the process variable changes, causing the measured value to change. This difference between set point and the measured value causes an error signal to be sent to the controller. The controller output moves a correcting device to correct for the disturbance. This causes the process variable to return to a level where it equals the set point, thereby, cancelling the error signal to restore stable operation.

There are several system characteristics that define a good closed-loop system (i.e., how well the system reduces the error signal to zero or to almost zero). The final difference between the measured value and set point (stable operation) is called "offset".

- **A good system has a low offset.**

A second, and, possibly, more important characteristic is the speed with which a system responds or restores agreement.

- **A good system has a fast speed of response.**

Further, the system should be free of large and violent oscillation.

- **A good system is stable.**

With these characteristics in mind, it should be apparent that all systems cannot meet all requirements with a single type of controller. There are five recognized modes of control.

- ON-OFF control

  (Simple systems — LC function not required)

- Proportional control

  (Magnitude-oriented control)

- Proportional-plus-Integral (PI) control

  (Magnitude and error time duration oriented)

- Proportional-plus-Derivative (PD) control

  (Magnitude and error rate of change oriented)

- Proportional-plus-Integral-plus-Derivative (PID) control

  (Magnitude, error time duration, and error rate of change oriented)

These control modes increase in complexity from the top to the bottom of the list. Usually, the more difficult the control problem, the farther down the list the solution is found. Since ON-OFF control systems are generally not handled by the LC function, this control mode is not discussed in this document.

5-2. CONTROL MODES

5-3. PROPORTIONAL CONTROL ($M = K_C e$)

In the Proportional control mode, the final correcting device is operated over a continuous range of possible positions. The exact position is proportional to the error signal (i.e., the output of the controller is proportional to the error signal).

In the Proportional control system shown in Figure 5-6, the final correcting device is a variable position valve controlling the fuel supply to a burner that is used to heat a product passed through a combustion chamber. The system operates as follows: when the valve opens, the temperature increases; when the valve closes, the temperature decreases. Assume that the controller is set up such that when the temperature of the product is 190°F or higher, the controller will fully close the fuel valve, and when the temperature is 165°F or lower, the controller will fully open the fuel valve. The system, however, may be assumed to be operating at a steady-state temperature of 180°F and the valve 40 percent open. (Due to the many unpredictable factors in maintaining operation at 180°F, actual valve position cannot be predicted; therefore, 40 percent is an assumption.) Figure 5-7 shows the conditions defined for this sytem.

Assume that a change causes the measured temperature to drop to 175°F. The valve will open to 60 percent of its range, causing temperature to rise accordingly. If the change had been larger (to 170°F), the valve would have opened to 80 percent of its range. This change illustrates the proportional nature of the system. A 5°F drop in temperature results in a 20 percent increase in valve opening; a 10°F drop in temperature results in a 40 percent increase in valve opening (i.e., doubling the error doubles the response, a proportional reaction.)

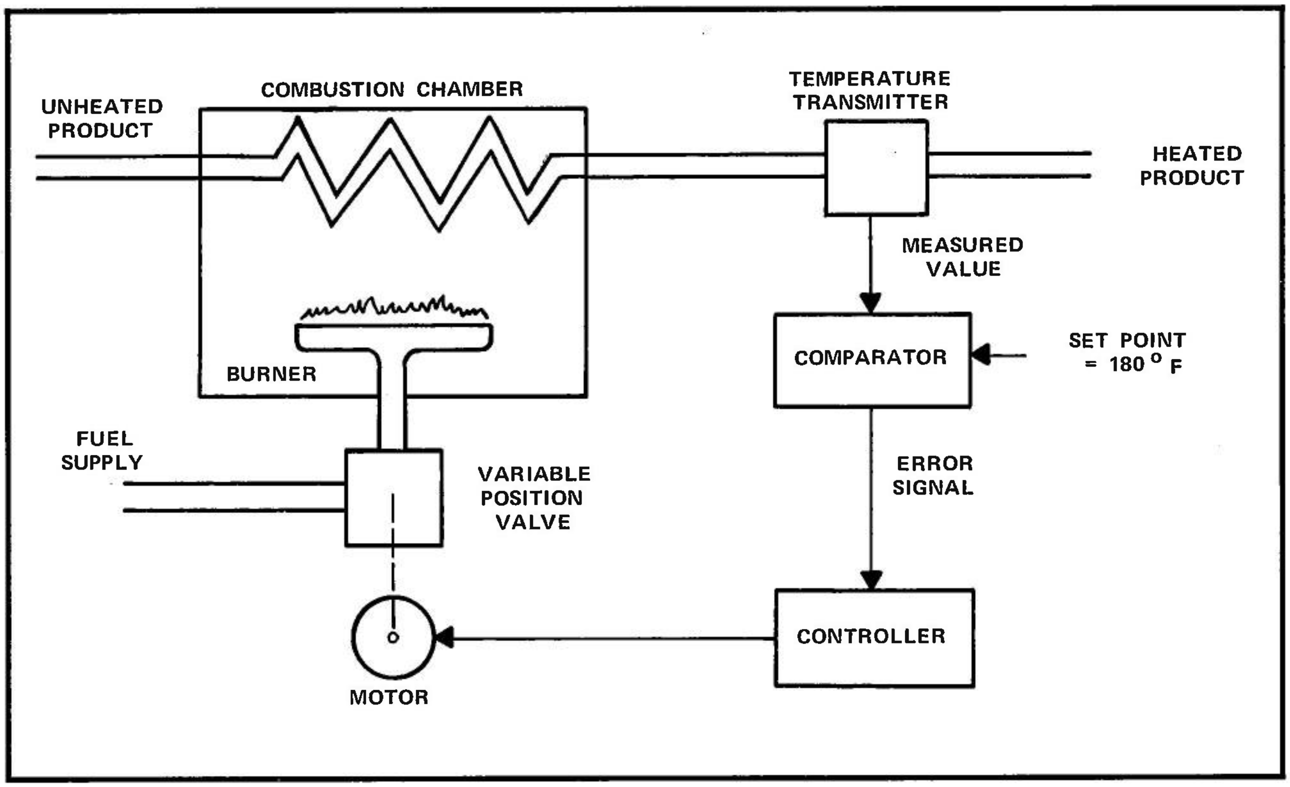


Figure 5-6. Proportional Control System

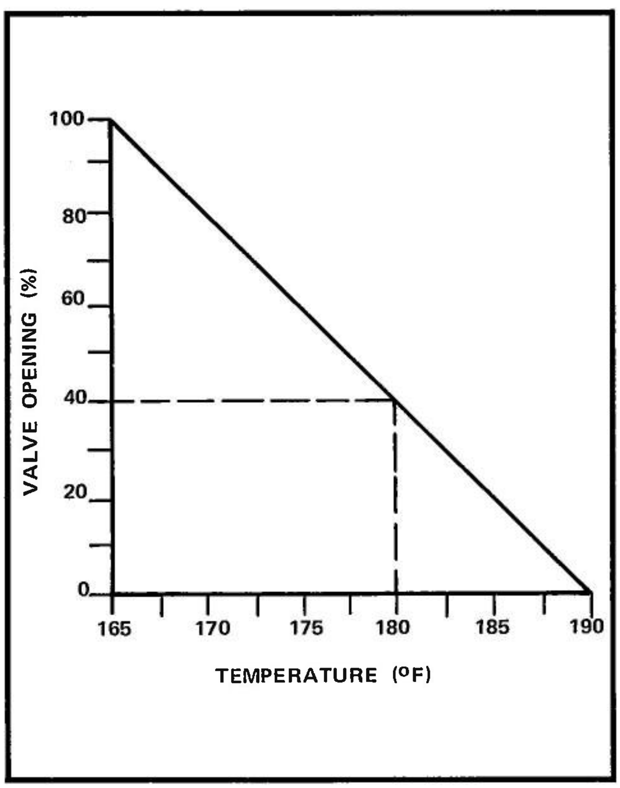


Figure 5-7. Operating Range/Set Point

5-4. PROPORTIONAL BAND

Figure 5-7 shows that the valve is fully-open at 165°F and fully-closed at 190°F (a range of 25°F). This range is called the proportional band of control. Within this band of temperature, valve response is proportional to temperature change. Proportional band is expressed as a percentage of full scale range of the controller. If, for example, the set point can be between 60°F and 300°F, the proportional band is:

$$\frac{25\,°F}{(300\,°F - 60\,°F)} = 0.104 = 10.4 \text{ percent}$$

Formally defined, **proportional band is the percentage of full controller range by which the measured value must change to cause the correcting device to change by 100 percent.** Since the proportional band is easily defined, we can derive the gain by using the following calculation:

$$\text{Gain } (K_C) = \frac{100}{P}$$

where:

P = proportional band, expressed as a percentage

Using the information given in Figure 5-7:

$$\text{Gain } (K_c) = \frac{100}{10.4} = 9.62$$

The system shown in Figure 5-7 can then be said to have a proportional band of 10.4 percent and a proportional gain of 9.62. Given the same proportional band and the same operating condition of 180°F, conditions may be such that a 60 percent valve opening is required to maintain 180°F. The slope of the graph would be the same as in Figure 5-7, but the upper and lower limits will have changed (i.e., increased by 5°F). (See Fig. 5-8.)

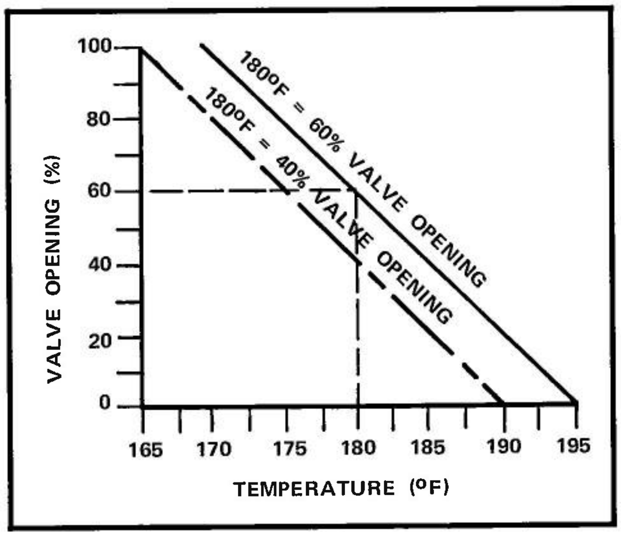


Figure 5-8. Operating Range/Set Point with Redefined Limits

Control will remain proportional, but the valve will now be fully-closed at a measured temperature of 195°F, and fully-open at a measured temperature of 170°F. Everything has shifted upward accordingly.

Proportional control tends to eliminate permanent system oscillations found in more simple ON-OFF control schemes (such as that shown in Figure 5-3). Oscillations are still possible, but they should tend to die out. It is also possible to set the proportional band narrow enough to cause the system to act (and oscillate) as if it were an ON-OFF system. A properly-designed Proportional control system is still relatively simple, but overcomes the inherent problems of oscillation and part wear found in ON-OFF systems.

Response in a Proportional control system is a function of proportional band. Consider the three response graphs shown in Figure 5-9.

In the system shown in Figure 5-6, different proportional band settings result in different responses.

Figure 5-9 shows system reaction to a set-point change, causing the temperature to change from T_1 to T_2. In (a), a relatively narrow proportional band setting of 10 percent shows that the system responds rapidly to changes, but oscillates once at the desired position. In (b), at 50 percent proportional band, the response is slower, with less oscillation. Finally, in (c), the response is much slower with no oscillations; control is smoother.

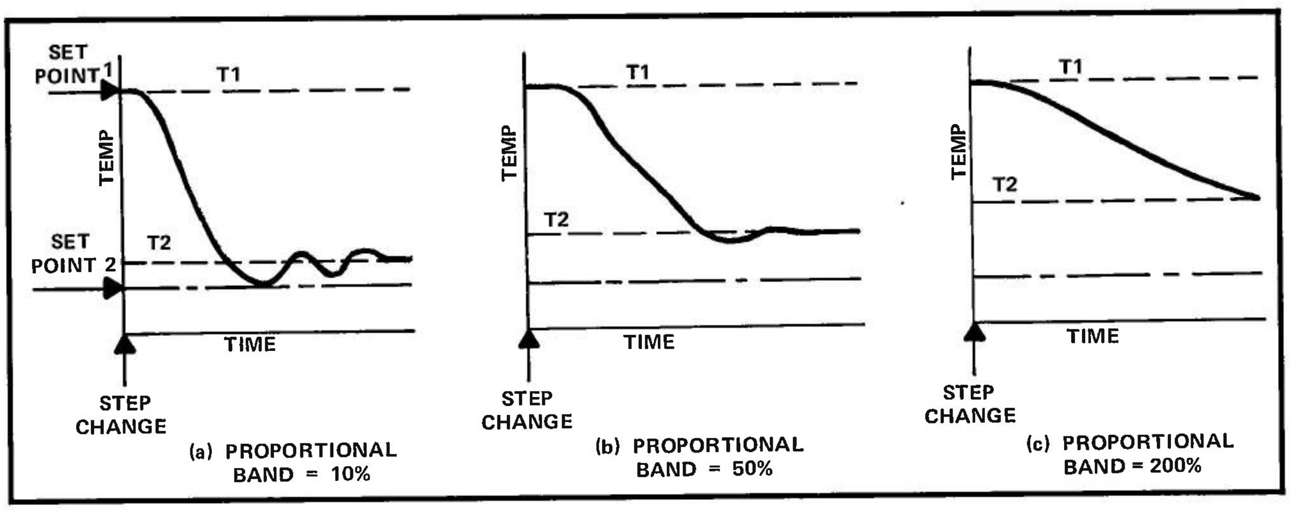


Figure 5-9. Effect of Proportional Band

5-5. STEADY-STATE ERROR (OFFSET)

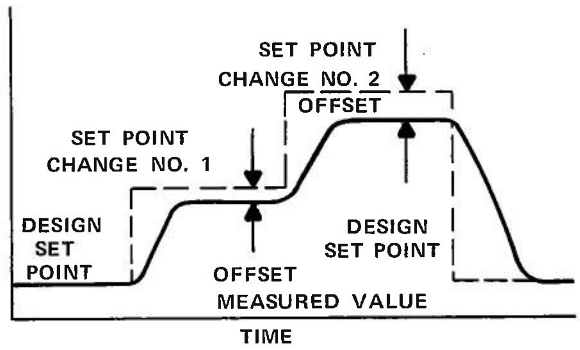
Refer again to the graphs of Figure 5-9. Note that in the plot of temperature versus time, the actual measured temperature does not reach the desired control value. The wider (larger) the proportional band, the greater the difference between the final temperature (T_2) and the new set point (Set Point 2).

To understand this effect, re-examine the operation of the proportional system used in Figure 5-6. When the controller is maintaining 180°F with a valve opening of 40 percent and a disturbance of some nature occurs causing the temperature to drop, the valve will drive open to increase the fuel flow to correct the drop in temperature. The control valve must now remain further open permanently to maintain heat at the desired level. Since the percentage of valve opening is proportional to the error signal, a permanently increased valve opening can only occur if there is a permanently increased error. Proportional systems tend to have a permanent error. The more narrow the proportional band, the smaller the error. Proportional systems work very well where changes are small and slow, allowing a very narrow proportional band, and a very small permanent error.

5-6. BIAS ($M = M_O + K_C e$)

In purely proportional control, $M = K_C e$. If e equals zero, M (the output) must also be zero. To achieve a zero error with a non-zero output, we must introduce a bias term, M_O, such that M equals M_O at e equals zero. Assume that a zero error signal occurs when the valve is 40 percent open and the temperature is 180°F. If the system was started, the error signal is a large negative value and the valve would be open more than 40 percent. This implies a 40 percent bias. As the temperature more closely approaches 180°F, the more closely the valve approaches 40 percent open, and the system becomes stable at 180°F. In this sytem, this is the only possible set point at which there will be a zero error. To have a zero error, a unique value of M_O (bias) must be chosen for each unique set point. If M_O is constant at 40 percent, and a new set point is selected (e.g., 185°F), the valve would have to open more than 40 percent and the error signal can no longer be zero. Actual measured temperature could not quite reach 185°F to maintain the error necessary to keep the valve open more than 40 percent. This difference is the **offset** and the farther the set point is from the "zero-error" set point, the worse the offset.

Consider the graph shown in Figure 5-10.



NOTES

1. THE SET POINT IS REPRESENTED BY THE DASHED LINE.
2. THE MEASURED VALUE IS REPRESENTED BY THE SOLID LINE.

Figure 5-10. Offset Effect

As shown, the proportional system operates without offset when it is operating at the exact design set point. If the set point is changed for any reason, offset occurs, increasing in size as the difference between the design set point and new set point increases. Offset results in a constant error signal (set point minus measured value) for all conditions other than the design set point. Strict proportional control can be best used where load changes are small and low, and set point variation is small.

5-7. PROPORTIONAL-PLUS-INTEGRAL (PI) CONTROL ($M = K_C e + K_I I$)

Systems subject to large changes do not function well in a purely Proportional mode due to this offset problem. The method of overcoming the offset problem is to have an automatic function that senses the offset and continuously recalculates the bias such that the error can be zeroed (see Fig. 5-11).

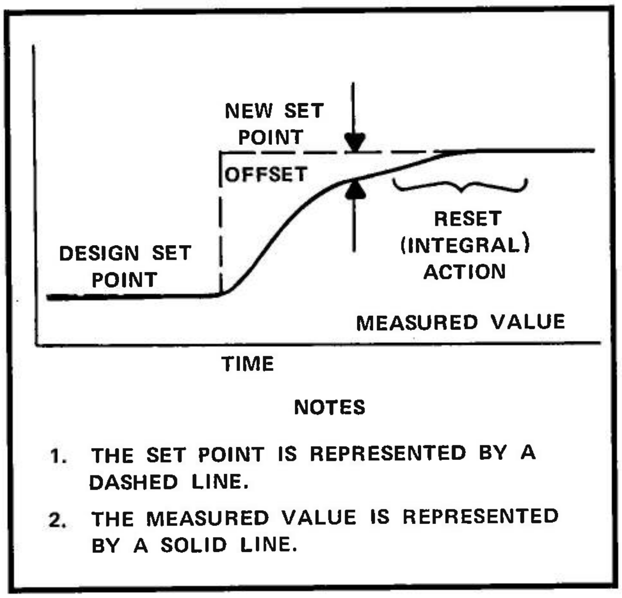


Figure 5-11. Integral Control

To achieve this function, the time integral of the error signal (magnitude of the error multiplied by the time it has persisted) assists in determining the final valve (operating) level. This is Proportional-plus-Integral (PI) or Proportional-plus-Reset control. The proportional part positions the correcting device in proportion to the error that exists; then, the integral (or reset) part senses the offset that remains and continues motion of the correcting device in the same direction until the offset is reduced. In most applications, the integral time is not used directly; rather, the reciprocal of integral time is used and is termed the reset rate.

When the reset rate is low (large time constant), the integral part is slow to make its effects felt on the process.

The PI mode of control can handle most process control situations. Large loads and large variations in set point can be controlled efficiently with no prolonged oscillation, no permanent offset, and relatively quick recovery after an upset.

PI control can handle all control situations, except those having very rapid load changes and a long time lag between application of the corrective action and appearance of the corrective action in the process variable measurement.

5-8. DERIVATIVE CONTROL

Since the derivative of any function is the measure of rate of change, this can be added to proportional control to cause the sytem to "overreact" to rapid (high rate of change) load variations. This is called derivative or rate control. These cases can be handled very effectively by the Proportional-plus-Integral-plus-Derivative (PID) control. In this mode, corrective action is determined as follows:

- Magnitude of the error (Proportional mode)
- Time duration of the error (Integral mode)
- Rate of change of the error signal (Derivative mode)

The effects of PID control are illustrated in Figure 5-12.

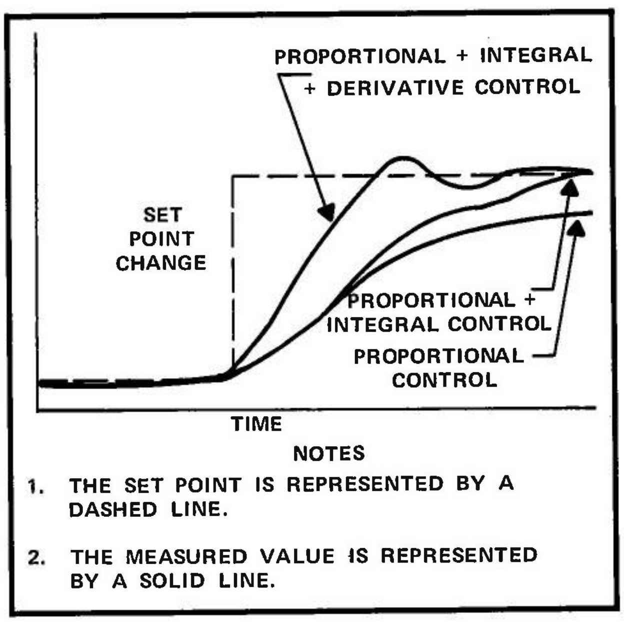


Figure 5-12. Effects of PID Control

The PID control mode efficiently controls systems with wide variable set points, large load changes, and rapid system fluctuation.

Proportional-plus-Derivative (PD) systems are rarely used in process control systems; however, they are useful in position (servo) control applications. In these situations, the system responds to both the magnitude and the rate of change of the signal (in a system that can find a true null). (See Fig. 5-13.)

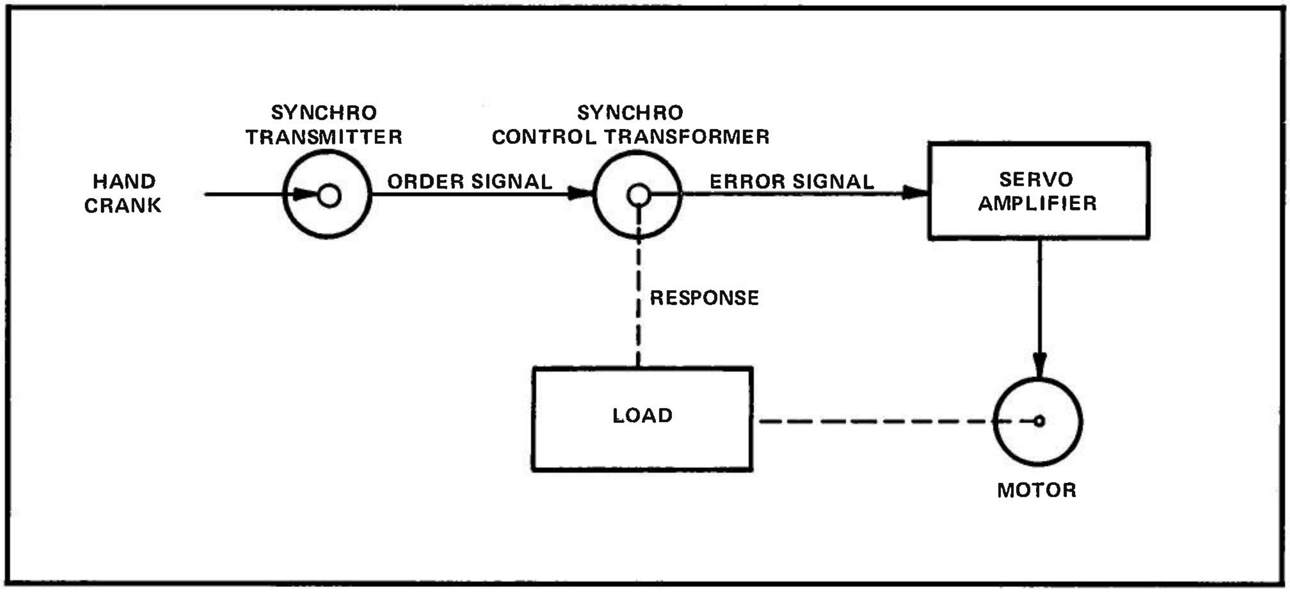


Figure 5-13. PD Control

In PD systems, an order signal is applied to the synchro control transformer, developing an error signal which is amplified, causing a motor to drive the signal to null by moving the rotor of the synchro control transformer. Using the PD mode allows faster response to large, rapidly changing position signals.

5-9. CLOSED-LOOP CHARACTERISTICS

5-10. REACTION DELAY

In selecting a mode of process control, it is necessary to consider not only control system characteristics, but also the reaction of the process itself. Most processes require a certain amount of time to fully respond to a change in input. This amount of time is called process reaction delay and must be considered when selecting a mode of control. Another factor that must be considered is "transfer lag", a condition in which the corrective action must be transferred through one (or more) other media before affecting the process variable. The difference between process reaction delay and transfer lag is in the manner of application of correction to the process. All systems have some form of process reaction delay, but systems in which corrective action is transferred from medium to medium before application to the process also suffer additional transfer lag. Process reaction delay is easily predictable; transfer lag is not. Long **transfer** lags constitute a difficult control problem. An additional, and more difficult, problem is that of **transportation** lag or dead time (or combination of both). This situation occurs when nothing occurs for some period of time after application of a correction. This situation results from delays due to the requirement that some part of the process may be physically transported from one place to another (hence "transportation" lag). In geared mechanical systems, this is known as "lost motion" (i.e., the amount of motion required to take up the slack in a gear train). All these factors must be considered in selecting a control mode. Table 5-1 is helpful in selecting a control mode.

It is apparent from Table 5-1 that the PID control mode is a mode for all conditions, and its use can almost always be justified.

5-11. TUNING

Three characteristics must be adjusted (tuned) in the controller for proper system operation:

- Proportional band
- Reset rate (reciprocal of integral time constant)
- Derivative control rate

TABLE 5-1. CONTROL MODES

Control Mode	Process, Reaction Delay (Minimum)	Transfer Lag (Maximum)	Dead Time (Maximum)	Size of Load Upset (Maximum)	Speed of Load Upset (Maximum)
Proportional	Long or moderate (cannot be short)	Short or moderate	Short or moderate	Small	Slow
Proportional-plus-Integral (PI)	Any	Short or moderate	Short or moderate	Any	Slow
Proportional-plus-Derivative (PD)	Long or moderate (cannot be short)	Short or moderate	Short or moderate	Small	Any
Proportional-plus-Integral-plus-Derivative (PID)	Any	Any	Any	Any	Any

These adjustments depend on the process and the mode of control. In a PI control system, the tuning of the system is dependent on the process characteristics shown in Table 5-2.

Reaction rate is the opposite of reaction delay. A short reaction delay equates to a fast reaction rate. A PD control system must have a moderate to long reaction delay and a narrow proportional band, because there is no integral control to take care of the offset. The narrow proportional band is subject to overshoot and cycling, but the derivative portion of the controller tends to overreact whenever the error is changing rapidly, thus stabilizing the system within the proportional band.

When long transfer lags and/or long dead times are present, PID control is nearly always the only successful scheme of control. In PID control, the proportional band is very wide such that only a small portion of corrective action after an upset is due to proportional control. Most immediate reaction is due to the derivative portion of the controller so that when the error stops growing, derivative action disappears, leaving only the small signal. Due to proportional action, the controller senses recovery, and the integral portion of the controller repositions the system back to the original set point.

5-12. ALARMS

In closed-loop systems, alarms are generally used on the process variable and are either fixed points within the operational span of the system (see Fig. 5-14) or are in a band about, and moving with, the set point (see Fig. 5-15). Fixed alarms are called the high and low limit alarms; alarms moving with the set point are called deviation alarms. Deviation alarms apply equally to either side of the set point; there are two low-deviation alarms (one on either side of the set point), and two high-deviation alarms (one on either side of the set point, and a greater distance from the set point than the low-deviation alarm). Each alarm of either type has an associated programmable deadband on the side toward the desired operating range. The deadband is used to prevent alarm "chatter".

The high alarm comes ON when the process variable exceeds the high alarm limit and goes OFF when the process variable is less than the high limit deadband. Further, high and low alarm limits, unlike deviation alarms, do not change with set point.

5-13. BATCH UNIT

A batch unit is used to start batch processes automatically. Without batch limits, starting a process from a cold start subjects the system to excessive error signals with a resultant large overshoot in the process variable.

TABLE 5-2. CONTROLLER TUNED REACTION RATES

Process Characteristic		Controller Tuning	
Reaction Rate	Total Lag	Proportional Band	Reset Rate (Reciprocal of Integral Time Constant)
Slow	Short	Narrow	Fast
Slow	Moderate	Medium	Slow
Fast	Short	Medium	Fast
Fast	Moderate	Wide	Slow

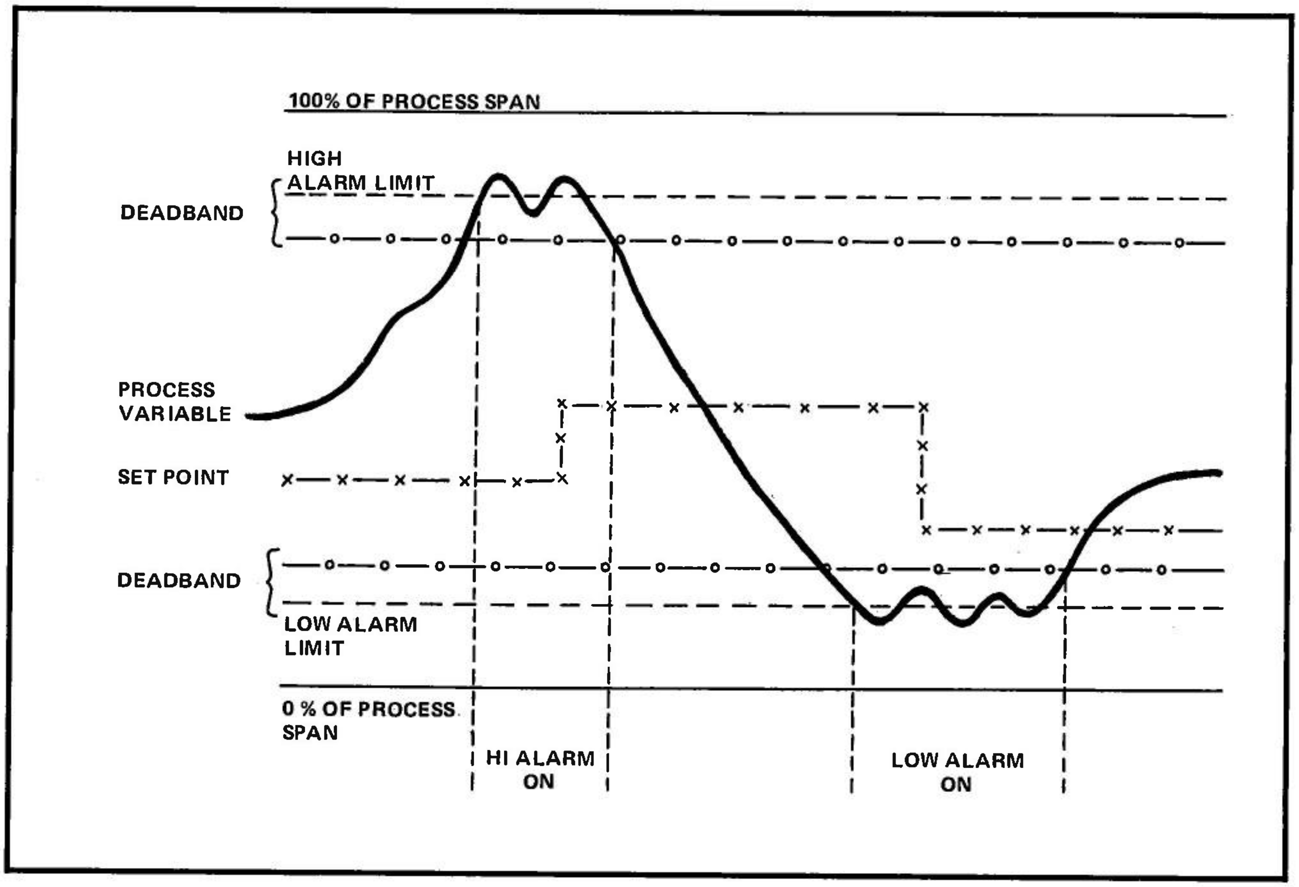


Figure 5-14. High and Low Limit Alarms

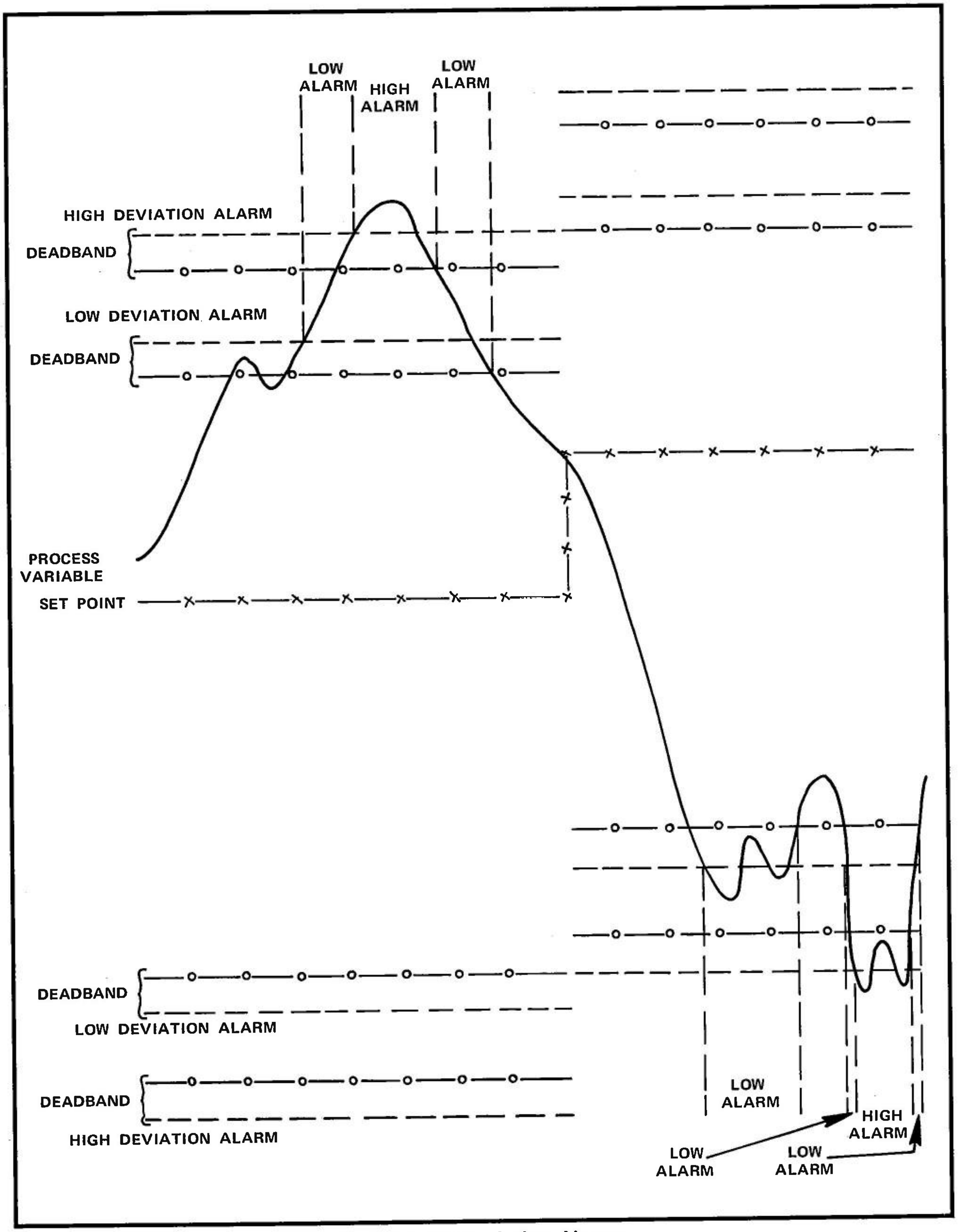


Figure 5-15. Deviation Alarms

Batch control establishes both a minimum output and a maximum output such that no matter how high the output may try to go, it is limited to an acceptable value by the batch unit high limit. Likewise, the batch unit preload ensures that the output cannot fall below a preload value. This feature provides rapid stabilization of batch processes. Batch limits are also used on the **Numa-Logic** LC to allow user-selection of 10- or 12-bit D-A converters without unnecessarily winding up the integral (reset) term. (See Fig. 5-16).

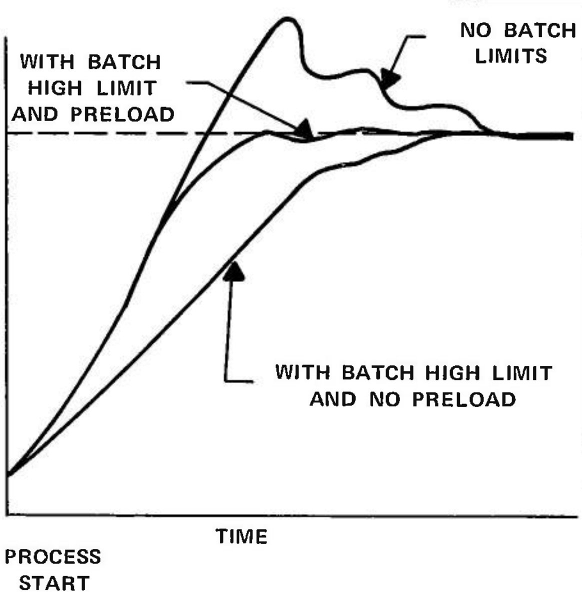


Figure 5-16. Batch Limit Effects

5-14. ERROR-SQUARED CONTROL

In some closed-loop applications, the controller must demonstrate low gain for small error signals, and high gain for large error signals. The solution for this problem is to provide a mode in which the controller operates as a function of the square of the error signal. This means that the controller sees an error signal that seems to change as indicated in Figure 5-17. The system responds as if it had variable gain; small signals closely approximate the response from an unmodified error signal, while increasingly large error signals cause a increasingly large response. (The error is not squared, but its absolute magnitude is used to multiply gain, thereby, having the same general effect.)

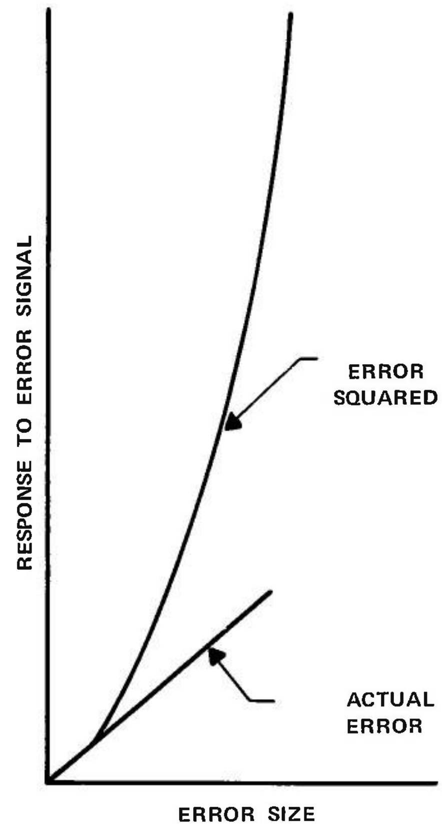


Figure 5-17. Error-Squared Control

5-15. ERROR DEADBAND

Error deadband control is used to eliminate response to small error values. A deadband is established about the set point (using the low-deviation limit to set the deadband) in which error values have no effect and are treated as zero error. Beyond the deadband limits, the deadband value is subtracted from the actual error to get a "computed error", which is actually used in loop calculations. Figure 5-18 shows the effects of error deadband.

An error signal is computed only when the actual error signal exceeds the deadband (low-deviation alarm) values. The apparent result is no response to small errors and reduced response to larger errors.

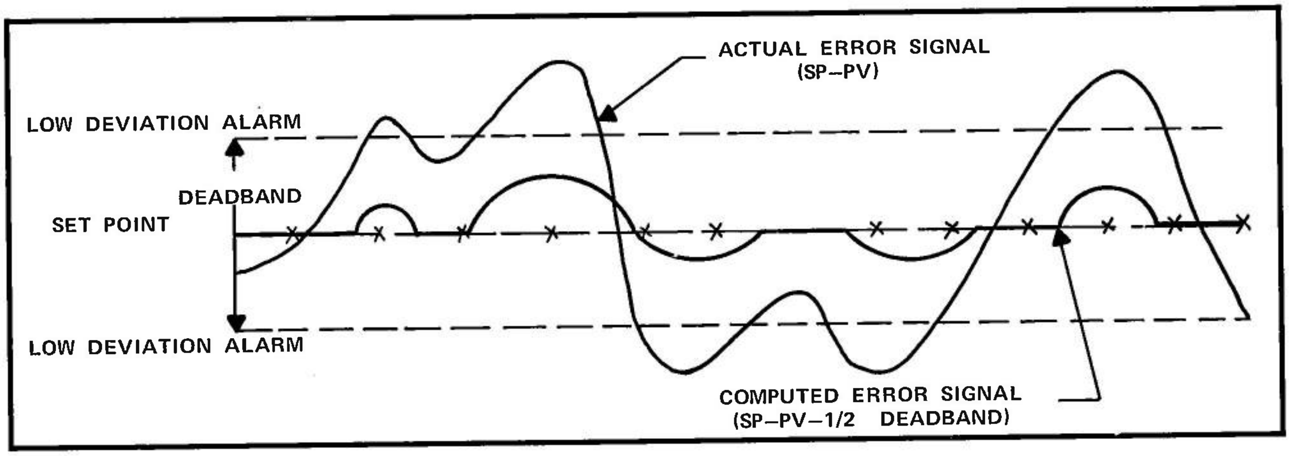


Figure 5-18. Effect of Error Deadband

5-16. SAMPLE TIME

Process control is done in an interactive fashion. Of critical importance to the user are the maximum and minimum times between samples (loop calculations). The **Numa-Logic** LC function has a programmable sample time of 0.1 second to a maximum of 3276.7 seconds in 0.1 second increments. The user generally selects sample time as a function of the actual system response times.

5-17. ANTI-RESET WINDUP

The integral term of a closed-loop system tries to continue increasing the loop output as long as there is a deviation from the set point. If that deviation cannot be eliminated, or if the deviation persists for a long period of time, the integral error accumulates, causing the output of the loop to maximize and remain maximized.

Once the output has maximized, there is no use in continuing to increase the contribution of the integral term. Conversely, once the output is zero, it is of no use to continue decreasing (increasing in a negative direction) the integral term. This is known as reset windup and is generally undesirable. The LC function has programmable batch unit high limit and preload values. If the output is outside these limits, the LC limits the output to the appropriate batch limit, then back calculates the reset term so that the batch unit high limit or preload is not exceeded. This is anti-reset windup. Anti-reset windup is also used to accommodate slew-limiting, described in the following paragraph.

5-18. SLEW-LIMITING

It may be desirable to limit the rate at which the controller output may change (slew). This feature is called slew-limiting and prevents the rate of change of the output from exceeding preset limits (see paragraph 5-17). The **Numa-Logic** slew-limiting term represents the maximum acceptable change in controller output in any given sample, as specified by the sample timer.

5-19. REMOTE SET POINT

Generally, the set point for a system is entered from an operator station; however, sometimes it is necessary to accept a set point from another device. Conventional controllers require the purchase of a remote set-point option. Since the **Numa-Logic** Programmable Controller can accept a set point from an internal or external register source, this can be accomplished without such an option. The user can either program the programmable controller to perform the operations of the external device (for example, a cam timer) or condition the signal of an external device to provide a satisfactory input to the loop. This also facilitates cascading of loops, where the output of one loop (the outer loop) feeds the set point of another loop (the inner loop).

5-20. CASCADE

The Cascade mode of operation is used when it is desired to control one loop with the output of another loop. Figure 5-19 shows a Cascased closed-loop system. In this system, hot water is heated by using steam. The system operates as follows:

1. A decrease in water temperature causes the output of the temperature controller to indicate a need for an increase in temperature.

2. This output is the set point for the flow controller and results in an increase in the set point, indicating the need for more steam flow.

3. The flow controller increases the amount of steam until the process variable (flow) indicates that the need is satisfied, which also means that the water temperature is high enough to satisfy the set point for the temperature controller.

The use of Cascaded loops allows the flow controller to compensate for changes in steam pressure before that change affects the actual temperature, making a much tighter control system. A temperature controller alone would have compensated for steam pressure fluctuations, but only after it sensed a change in temperature.

5-21. BUMPLESS TRANSFER

The term "bumpless transfer" means that transfers for the Auto mode to Manual (or vice versa) and setting up Cascaded loops are accomplished without system upset. This is done by using an internal Auto bias system such that when a transfer is made from one mode to another, no changes in system output are made. For example, when the transition is made from the Manual to Auto mode, the output is held constant; the integral term is reset; and SP_n (the set point in this sample) is set equal to PV_n (the process variable in this sample) to zero the error. Finally, the bias term is set equal to the output value (this is known as Auto bias). This "balances" the PID equation such that no "bump" occurs.

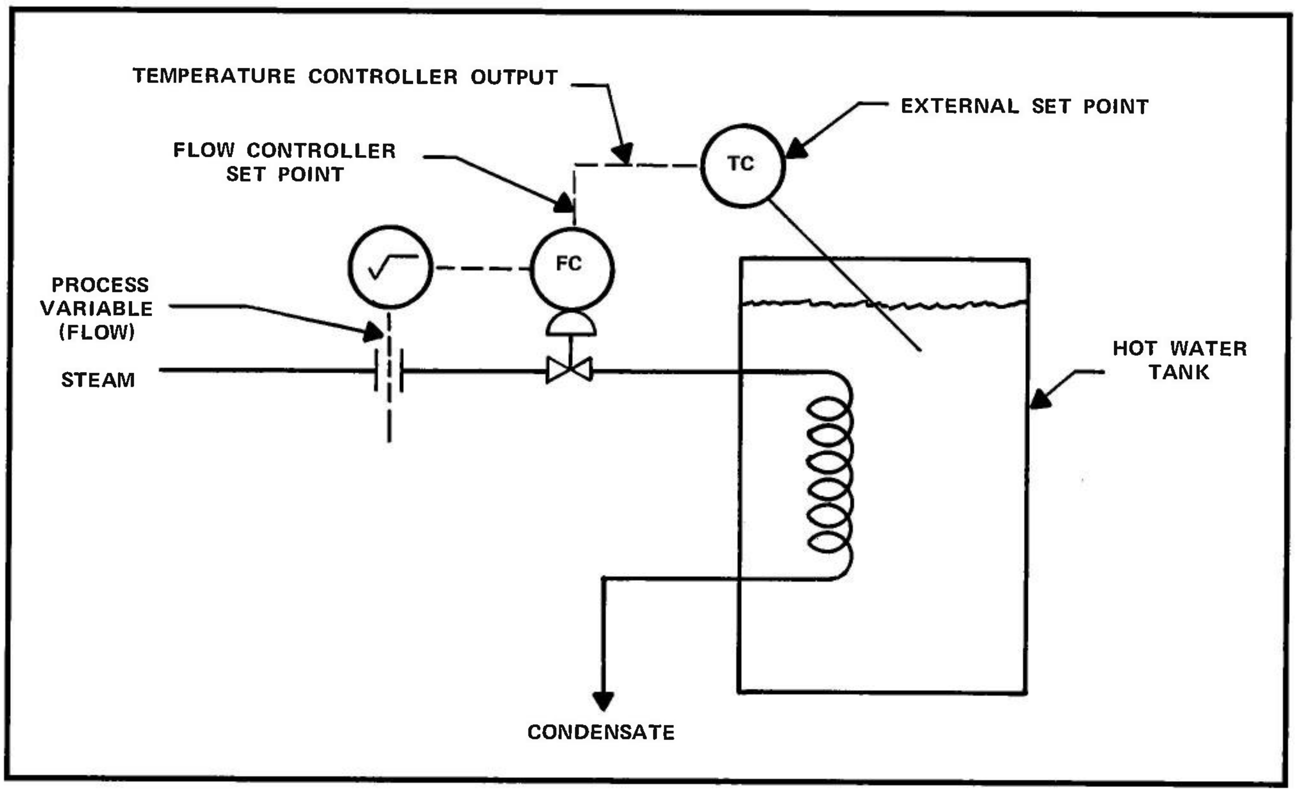


Figure 5-19. Cascaded Systems

5-22. LOOP CONTROL WITH A PROGRAMMABLE CONTROLLER

5-23. FUNCTIONAL DESCRIPTION

The preceding general discussion of closed-loop control systems revolves around the general block diagram of Figure 5-5. By using a programmable controller, that block diagram is modified as shown in Figure 5-20.

System development is reduced to:

- Selecting the appropriate transducers, transmitters, process operators, etc.
- Selecting the control mode.
- Setting the system limits.
- Tuning the system.

In **Numa-Logic** Programmable Controllers, the LC function is programmed as a special function and is very memory efficient (i.e., the loop table uses 32 words; a special function uses six words; and the control circuit uses a minimum of four words). (See Table 5-3.) The **Numa-Logic** Programmable Controllers can be used effectively in process control by coupling this efficiency with a wide range of analog and register modules. The symbols and basic concepts involved with the LC function are shown in Figure 5-21. An LC data worksheet is shown in Table 5-4. A blank data worksheet is provided at the end of Section 5; copy as needed.

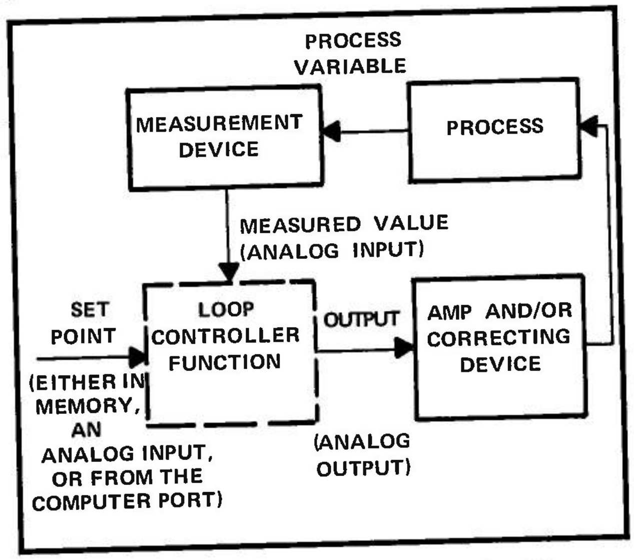
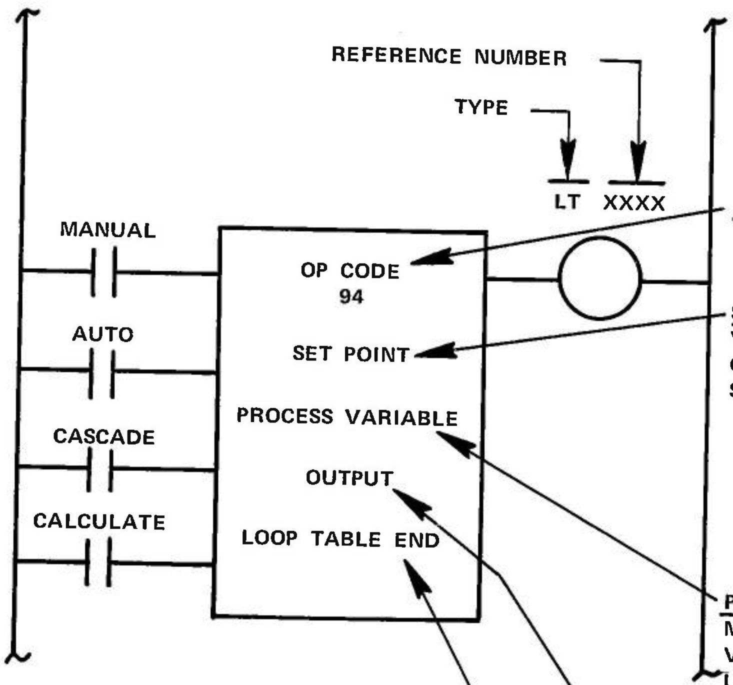


Figure 5-20. Closed-Loop Control with a Programmable Controller

TABLE 5-3. OUTPUT STATUS WORD (HRXXXX)

Bit Number	Definition	Bit Number	Definition
1	1 = High alarm limit active	9	1 = Record Auto/Manual
2	1 = Low alarm limit active	10	1 = Record Cascade
3	1 = High-deviation alarm active	11	1 = Illegal request — wrong mode
4	1 = Low-deviation alarm active	12	Reserved for future use
5	1 = Sign of error — negative 0 = Sign of error — positive	13	Reserved for future use
6	1 = Positive slew-limiting	14	Reserved for future use
7	1 = Negative slew-limiting	15	Reserved for future use
8	1 = Error-squared overflow on gain $(K_c) \bullet e_n \geqslant 99.99$	16	Reserved for future use



COIL STATUS = ALARM
LOW ALARM LIMIT
HI ALARM LIMIT
LO DEVIATION
HI DEVIATION

OP CODE 94. DEFINES THE LITERAL (LT) FUNCTION AS BEING A LOOP CONTROLLER (LC) FUNCTION.

SET POINT. THIS VALUE IS THE DESIRED VALUE OF THE PROCESS VARIABLE. THIS CAN BE A CONSTANT VALUE OR BE STORED IN A SPECIFIED:

- HOLDING REGISTER (HR)
- INPUT REGISTER (IR)
- OUTPUT REGISTER (OR)
- INPUT GROUP (IG)
- OUTPUT GROUP (OG)

PROCESS VARIABLE. THIS IS THE MEASURED VALUE OF THE INDEPENDENT VARIABLE INVOLVED IN THE PROCESS UNDER CONTROL. THIS CAN BE STORED IN A SPECIFIED:

- HOLDING REGISTER (HR)
- INPUT REGISTER (IR)
- OUTPUT REGISTER (OR)
- INPUT GROUP (IG)
- OUTPUT GROUP (OG)

OUTPUT. THIS IS THE OUTPUT OF THE PROCESS CONTROLLER USED TO DRIVE THE FINAL CORRECTING DEVICE TO ADJUST THE PROCESS UNDER CONTROL. THIS CAN BE STORED IN A SPECIFIED:

- HOLDING REGISTER (HR)
- OUTPUT REGISTER (OR)
- OUTPUT GROUP (OG)

LOOP TABLE END. THIS SPECIFIES THE LAST HOLDING REGISTER IN THE TABLE CONTAINING DATA REQUIRED FOR LOOP CONTROL OPERATIONS. THIS MAY NOT BE LESS THAN HR0032 NOR GREATER THAN THE HIGHEST HOLDING REGISTER AVAILABLE IN THE GIVEN PROCESSOR. THIS TABLE IS ALWAYS 32 HOLDING REGISTERS LONG. (IN TABLE 5-4, HRXXXX-31 IS THE BEGINNING OF THE TABLE AND HRXXXX IS THE END OF THE TABLE.)

TO ACTIVATE MANUAL/AUTOMATIC CASCADE MODES, IT IS NECESSARY TO CLOSE THE APPROPRIATE CONTACT FOR AT LEAST ONE SCAN.

THE CALCULATE INPUT MUST BE CLOSED TO CAUSE THE LOOP TO OPERATE.

Figure 5-21. LC Function

TABLE 5-4. LC DATA WORKSHEET

Loop Title:		C V	H R	I R	O R	I G	O G	Register Type & No. (Data If CV)	Comment
	Set Point	•	•	•	•	•	•		
	Process Variable		•	•	•	•	•		
	Output		•		•		•		
Loop Coil #:	Loop Table End		•						

Loop Table Register Positions	Loop Table Actual HR Assignment	Quantity		Value/Remarks
HRXXXX-31		Proportional Term (± 32,767)	C	
HRXXXX-30		Integral Term (± 32,767)	C	
HRXXXX-29		Derivative Term (± 32,767)	C	
HRXXXX-28		SP_n — Set Point This Sample	C	
HRXXXX-27		PV_n — Process Variable This Sample	C	
HRXXXX-26		Time Counter — Elapsed Sample Time	C	
HRXXXX-25		SP_{n-1} — Set Point Previous Sample	C	
HRXXXX-24		PV_{n-1} — Process Variable Previous Sample	C	
HRXXXX-23		E_{n-1} — Error Previous Sample	C	
HRXXXX-22		Bias (0 to Maximum Output)	C	
HRXXXX-21		RESERVED		FUTURE — DO NOT USE
HRXXXX-20		Configuration Input Word (See Below)	U	
HRXXXX-19		RESERVED		FUTURE — DO NOT USE
HRXXXX-18		RESERVED		FUTURE — DO NOT USE
HRXXXX-17		Integral Sum (± 32,767)	C	
HRXXXX-16		E_n — Error This Sample	C	
HRXXXX-15		T_d — Derivative Time (0 — 327.67 Min.)	U	
HRXXXX-14		T_i — Integral Time (0 — 327.67 Min.)	U	
HRXXXX-13		T_s — Sample Time (0 — 3276.7 Sec.)	U	
HRXXXX-12		K_c — Proportional Gain (.01 — 99.99)	U	
HRXXXX-11		Inner Loop Pointer (Loop Table End)	U	
HRXXXX-10		Outer Loop Pointer (Loop Table End)	U	
HRXXXX-9		Alarm Deadband (0 — Max PV)	U	
HRXXXX-8		Batch Unit Preload (0 — Max Output)	U	
HRXXXX-7		Batch Unit Hi Limit (0 — Max Output)	U	
HRXXXX-6		Neg. Slew Limit (Max — ΔOutput/Sample)	U	
HRXXXX-5		Pos. Slew Limit (Max + ΔOutput/Sample)	U	
HRXXXX-4		Low Deviation Alarm Limit (0 — Max PV)	U	
HRXXXX-3		High Deviation Alarm Limit (0 — Max PV)	U	
HRXXXX-2		Low Alarm Limit (0 — Max PV)	U	
HRXXXX-1		High Alarm Limit (0 — Max PV)	U	
HRXXXX		Output Status Word	C	

C = Calculated by Processor
U = User-Entered

Configuration Input Word (HRXXXX-20)

16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1

Bit Number	Definition	Status	Bit Number	Definition	Status
1	1 = Proportional Mode Selected		9	1 = Derivative on PV Selected 0 = Derivative on Error Selected	
2	1 = Integral Mode Selected		10	1 = Batch Unit Selected	
3	1 = Derivative Mode Selected		11	RESERVED FOR CONTROLLER USE	
4	1 = Deviation Alarms Selected		12	0 = Anti Reset Windup When Slew Limit Occurs	
5	1 = Error Deadband Selected		13	RESERVED FOR FUTURE USE	
6	1 = Error Squared Control Selected		14	RESERVED FOR FUTURE USE	
7	1 = Slew Limiting Selected		15	RESERVED FOR FUTURE USE	
8	1 = Reverse Action Selected 0 = Direct Action Selected		16	RESERVED FOR FUTURE USE	

5-24. LC FEATURES

The LC function has the following features:

- Cascaded loops
- Remote set point
- Auto/Manual/Cascade control with bumpless transfer
- Direct or reverse acting
- Auto bias
- Anti-reset windup
- Error-squared control
- Slew-limiting
- High and low alarms
- Deviation alarms
- Error deadband
- Calculate dpv/dt or de/dt

5-25. LC OPERATION

The LC function has two methods of operation:

- **Calculate circuit not conducting**

  Alarms are processed if selected and enabled. The Manual mode is functional. Auto or Cascade modes are not calculated, but the timer is functional. On time out, the output is not updated until the calculated line is closed (conducting).

- **Calculate circuit conducting**

  Loop control is fully functional. If necessary, the calculate line can be used to stagger the calculation of several loops; this prevents the possibility of several loops being calculated during a given scan.

Mode selection is accomplished by momentarily energizing either the Manual, Auto, or Cascade request lines. This sets the appropriate Auto/Manual or Cascade bit in the Output/Status Word. If more than one request line is conducting during a given scan, the mode is selected as follows:

1. In all cases, the Manual contact takes precedence.
2. If an illegal closure is made without Manual involvement, the Last Valid State is maintained.
3. Allowable transitions are shown in Table 5-5.

5-26. LC CONFIGURATION

Loops are configured by first programming the LC special function, and then entering data into the loop table.

The LC configurations include:

- Bumpless transfer
- Anti-reset windup
- Error-squared control
- Slew-limiting
- Alarms
- Reverse-acting
- dpv/dt vs. de/dt
- Cascaded loops
- PID selection

Selection of these features (error-squared control through dpv/dt vs. de/dt) is accomplished by setting the appropriate bits in the Input/ Configuration Word.

Bumpless Transfer

There are four types of bumpless transfer:

- Manual to Auto

  The output is held constant; the integral term is reset; and SP_n (the set point in this sample) is set equal to PV_n (the process variable in this sample), zeroing the error. The bias term is set equal to the output value.

- Auto to Manual

  This is the same as for Manual to Auto. However, no further changes in output occur until acted upon by the operator.

TABLE 5-5. MANUAL LOOPS

START — BOTH LOOPS IN MANUAL	
Inner Loop	**Outer Loop**
1. Adjust the output until it is near the desired point.	1. Load the desired set point.
2. Set the inner loop to Auto.	
3. Set the inner loop to Cascade.	3. Set point is passed from the inner loop's output.
	4. Set the output loop to Auto.
Notes	
1. If the inner loop goes from Cascade to Auto, the outer loop goes from Auto to Manual automatically. 2. Loop Controllers will not go into Cascade operation unless the inner and outer loop pointers are in the loop table.	

- Auto to Cascade

  The current value of the output is transferred to the register location where the outer loop set point resides.

- Cascade to Auto

  The set-point value is retained until it is manually changed.

Anti-Reset Windup

Two limits are programmed by the user to tailor anti-reset windup to the particular system being controlled:

- Batch unit high limit

  This is the maximum possible value of loop output.

- Batch unit preload

  This is the minimum possible value of loop output.

If either limit is reached, the value E_i is back-calculated to maintain that output. This prevents the reset term from accumulating further error and saturating, or "winding up".

If anti-reset windup is not selected, the processor defaults to 4095 for batch unit high limit and zero for batch unit preload.

Error-Squared Control

The error-squared control, when selected, multiplies K_C by e to reduce the gain for the low error, while increasing the gain for the large error values. The product cannot exceed 99.99.

Note

Either the error-squared control or the error deadband may be selected, but not both.

Slew-Limiting (positive and negative rate-selectable)

When slew-limiting is selected, it limits the rate of change of output to a specified number of units per sample. When slew-limiting is active, the appropriate status flag is energized within the Output/Status Word.

Alarms

High alarm occurs when the process variable exceeds a preset high alarm limit. Low alarm occurs when the process variable is below a preset low alarm limit.

High-deviation alarm occurs if the process variable differs from the set point by a selectable high-deviation alarm limit. Low-deviation alarm is similar to high-deviation alarm, but has a (smaller) selectable difference.

1. Deviation alarms are not calculated while in the Manual mode. Low-deviation alarm limit locations in the loop table are used to specify error deadband values (if selected).
2. If a high, low, high-deviation, or low-deviation alarm is active, the coil turns ON to signify an alarm.
3. A small deadband should be programmed for all alarm limits to eliminate alarm oscillation. The user should set the alarm deadband values to be consistent with his process needs.

Reverse-Acting

Selection of reverse-acting causes the calculation of e = PV-SP, instead of e = SP-PV.

dvp/dt vs. de/dt

If set-point changes adversely affect the derivative term, selection of dpv/dt eliminates the effect of rapid set-point changes on the derivative term.

Cascaded Loops

The inner loop pointer (loop table end for the inner loop) and the outer loop pointer (loop table end for the outer loop) must be entered by the user. These pointers are used by the function to check permissable Auto/Manual/Cascade transfers and to pass set-point information between loops.

PID Selection

P, I, and D are independently selectable as part of the Input Configuration Word. This allows the selection of any PID combination; it also allows the user to change modes in an online fashion, while controlling a process.

5-27. LC APPLICATIONS

The system shown in Figure 5-22 uses steam to heat a liquid product. The temperature is maintained by a temperature control loop, which senses the temperature (process variable), compares it to the set point (error equals set point minus process variable), and through the temperature controller, changes the output to change the amount of steam allowed into the heating coil in the tank. The system operates in the Proportional mode. Implementing this system with a programmable controller results in a system similar to that shown in Figure 5-23.

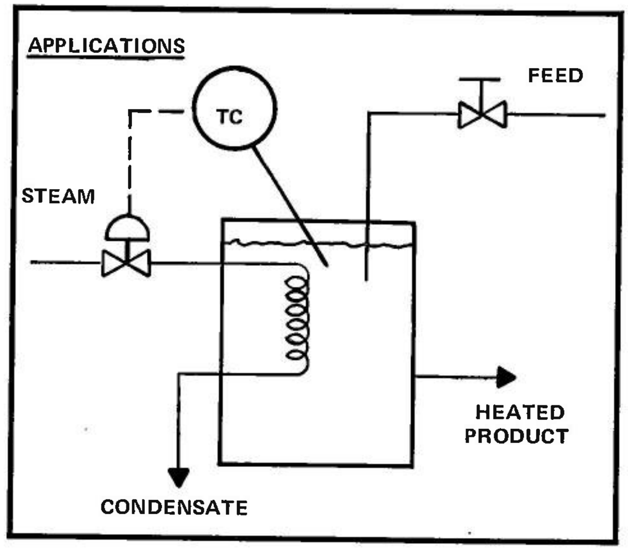


Figure 5-22. Single-Loop Control System

Assume that the temperature probe has a range of measurement from 0°C through 250°C. The process transmitter sends a 4 through 20 mA signal to the NL-740C Analog-to-Digital Converter. The A-D converter has a 12-bit resolution, dividing the 4 through 20 mA (0°C through 250°C) span into 4095 parts. Thus:

$$\frac{4095 \text{ units}}{250\,°\text{C}} = \frac{16.38 \text{ units}}{°\text{C}}$$

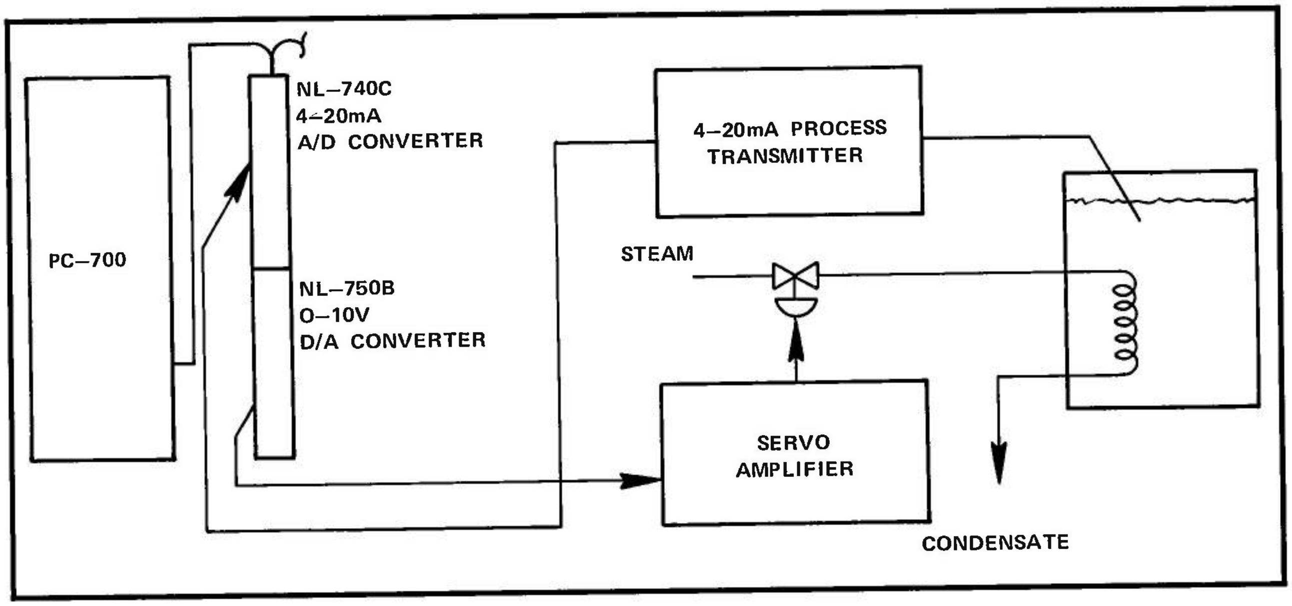


Figure 5-23. Single-Loop Hardware Configuration

If the set point of the system is to be 100°C, then the following calculation yields the number that must be placed in the set-point register corresponding to 100°C.

$$\frac{16.38 \text{ units}}{°C} \times 100°C = 1638 \text{ units}$$

The LC function, by using the set point and measured value of the process variable, develops an output to an output register for conversion to an analog voltage to control the valve position.

Since the output ranges from 0 percent through 100 percent of valve opening, the amount that the steam valve is open at any given time can be calculated by the following process:

$$\frac{\text{Number in Output Register for NL-750}}{4095} \times 100\% = \text{percentage of valve opening}$$

For example:

$$\frac{2135}{4095} \times 100\% = 52.13 \text{ percent open}$$

The loop can now be programmed as shown in Figure 5-24.

In Table 5-6, the high alarm limit is set to 4096 so that a high alarm will never be active for any output value.

Initially, an arbitrary figure is used for proportional gain. This arbitrary figure allows the system to operate such that the process can be lined out in the Manual mode. Once lined out, a tuning technique, such as that described later in this section, can be used to properly tune the gain.

Figure 5-25 extends the example shown in Figure 5-24.

This system uses three independent loops to control the temperature, liquid level, and flow.

Standard 4 through 20 mA process transmitters are used. The parameters of the system are:

- Temperature measuring device (100°C through 300°C)
- Flow measuring device (0 lpm through $(100)^2$ lpm)
- Level measuring device (0 cm through 500 cm)

TABLE 5-6. TEMPERATURE CONTROL LOOP (LT0001) DATA WORKSHEET

Loop Title: TEMPERATURE CONTROL LOOP		CV	HR	IR	OR	IG	OG	Register Type & No. (Data If CV)	Comment
	Set Point	•	•	•	•	•	•	HR0033	Set Point is Placed in
	Process Variable		•	•	•	•	•	IR0001	HR0033 Using a
	Output		•		•		•	OR0001	Program Loader
Loop Coil #: LT0001	Loop Table End		•					HR0032	

Loop Table Register Positions	Loop Table Actual HR Assignment	Quantity		Value/Remarks
HRXXXX-31	HR0001	Proportional Term (±32,767)	C	
HRXXXX-30	HR0002	Integral Term (±32,767)	C	Not Used
HRXXXX-29	HR0003	Derivative Term (±32,767)	C	Not Used
HRXXXX-28	HR0004	SP_n — Set Point This Sample	C	
HRXXXX-27	HR0005	PV_n — Process Variable This Sample	C	
HRXXXX-26	HR0006	Time Counter — Elapsed Sample Time	C	
HRXXXX-25	HR0007	SP_{n-1} — Set Point Previous Sample	C	
HRXXXX-24	HR0008	PV_{n-1} — Process Variable Previous Sample	C	
HRXXXX-23	HR0009	E_{n-1} — Error Previous Sample	C	
HRXXXX-22	HR0010	Bias (0 to Maximum Output)	C	
HRXXXX-21	HR0011	RESERVED		FUTURE — DO NOT USE
HRXXXX-20	HR0012	Configuration Input Word (See Below)	U	0001_H
HRXXXX-19	HR0013	RESERVED		FUTURE — DO NOT USE
HRXXXX-18	HR0014	RESERVED		FUTURE — DO NOT USE
HRXXXX-17	HR0015	Integral Sum (±32,767)	C	
HRXXXX-16	HR0016	E_n — Error This Sample	C	
HRXXXX-15	HR0017	T_d — Derivative Time (0 — 327.67 Min.)	U	Not Used
HRXXXX-14	HR0018	T_i — Integral Time (0 — 327.67 Min.)	U	Not Used
HRXXXX-13	HR0019	T_s — Sample Time (0 — 3276.7 Sec.)	U	100 Tenths of Seconds
HRXXXX-12	HR0020	K_c — Proportional Gain (.01 — 99.99)	U	5.00
HRXXXX-11	HR0021	Inner Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-10	HR0022	Outer Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-9	HR0023	Alarm Deadband (0 — Max PV)	U	Not Used
HRXXXX-8	HR0024	Batch Unit Preload (0 — Max Output)	U	0000 Default
HRXXXX-7	HR0025	Batch Unit Hi Limit (0 — Max Output)	U	4095 Default
HRXXXX-6	HR0026	Neg. Slew Limit (Max — ΔOutput/Sample)	U	Not Used
HRXXXX-5	HR0027	Pos. Slew Limit (Max + ΔOutput/Sample)	U	Not Used
HRXXXX-4	HR0028	Low Deviation Alarm Limit (0 — Max PV)	U	Not Used
HRXXXX-3	HR0029	High Deviation Alarm Limit (0 — Max PV)	U	Not Used
HRXXXX-2	HR0030	Low Alarm Limit (0 — Max PV)	U	0000
HRXXXX-1	HR0031	High Alarm Limit (0 — Max PV)	U	4096
HRXXXX	HR0032	Output Status Word	C	

C = Calculated by Processor
U = User-Entered

Configuration Input Word (HRXXXX-20)

16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Bit Number	Definition	Status	Bit Number	Definition	Status
1	1 = Proportional Mode Selected	1	9	1 = Derivative on PV Selected 0 = Derivative on Error Selected	0
2	1 = Integral Mode Selected	0	10	1 = Batch Unit Selected	0
3	1 = Derivative Mode Selected	0	11	RESERVED FOR CONTROLLER USE	0
4	1 = Deviation Alarms Selected	0	12	0 = Anti Reset Windup When Slew Limit Occurs	0
5	1 = Error Deadband Selected	0	13	RESERVED FOR FUTURE USE	0
6	1 = Error Squared Control Selected	0	14	RESERVED FOR FUTURE USE	0
7	1 = Slew Limiting Selected	0	15	RESERVED FOR FUTURE USE	0
8	1 = Reverse Action Selected 0 = Direct Action Selected	0	16	RESERVED FOR FUTURE USE	0

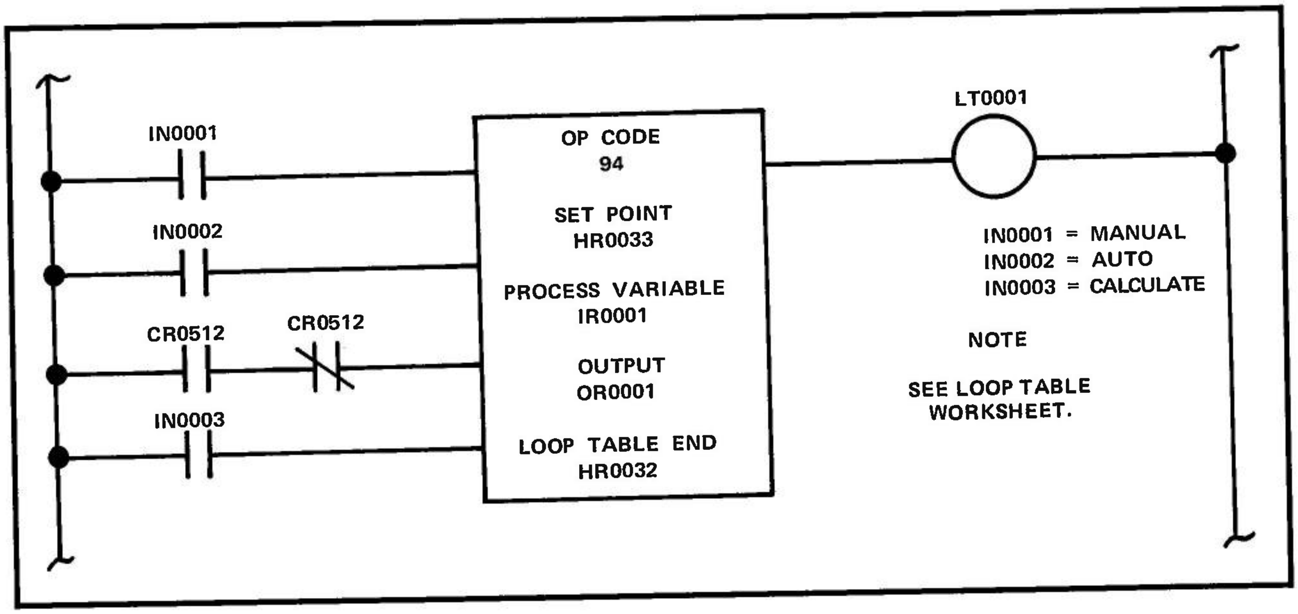


Figure 5-24. Loop Program

Since these inputs will be applied to an NL-742E A-D converter which has a 10-bit resolution, these input ranges must be converted to unit equivalents for use with the programmable controller. For the temperature loop:

$$\frac{1023 \text{ units}}{300^\circ C - 100^\circ C} = \frac{1023 \text{ units}}{200^\circ C} = \frac{5.115 \text{ units}}{^\circ C}$$

For the flow loop:

$$\frac{1023 \text{ units}}{(100)^2 \text{ lpm}} = \frac{0.1023 \text{ units}}{\text{lpm}^2}$$

Note

The processor will be required to take the square root of the flow input.

For the level control loop:

$$\frac{1023 \text{ units}}{500 \text{ cm}} = \frac{2.046 \text{ units}}{\text{cm}} = \frac{2 \text{ units}}{\text{cm}}$$

The programmable controller configuration of the system is shown in Figure 5-26.

In addition to the measuring devices, the temperature loop and flow loop have deviation alarms, and the level control loop has high and low alarm limits.

In the temperature loop, the low-deviation alarm limit is ± 10°C (set point ± 10°C), while the high-deviation alarm limit is ± 20°C (set point ± 20°C). A deadband of 2°C will be set for these limits. The settings are:

- Low-deviation alarm limit

  $$10^\circ C \times \frac{5.115 \text{ units}}{^\circ C} = 51.15 \text{ units}$$
  $$= 51 \text{ units}$$

- High-deviation alarm limit

  $$20^\circ C \times \frac{5.115 \text{ units}}{^\circ C} = 102.3 \text{ units}$$
  $$= 102 \text{ units}$$

- Alarm deadband

  $$2^\circ C \times \frac{5.115 \text{ units}}{^\circ C} = 10.23 \text{ units}$$
  $$= 10 \text{ units}$$

These values will be used in the loop table worksheet.

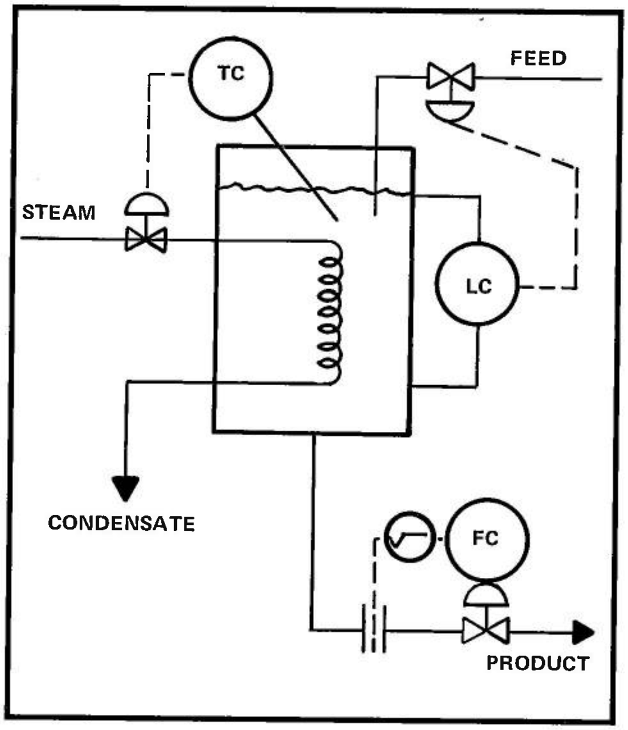


Figure 5-25. Three-Loop System

The flow loop will have a low-deviation alarm limit of ±20 lpm (set point ±20 lpm), a high-deviation alarm limit of ±40 lpm (set point ±40 lpm), and a deadband of 5 lpm. The settings are:

- Low-deviation alarm limit

$$\frac{0.1023 \text{ units}}{\text{lpm}^2} \times 20 \text{ lpm} = 6.425$$
6 units

- High-deviation alarm limit

$$\frac{0.1023 \text{ units}}{\text{lpm}^2} \times 40 \text{ lpm} = 12.7937$$
13 units

- Alarm deadband

$$\frac{0.1023 \text{ units}}{\text{lpm}^2} \times 5 \text{ lpm} = 1.59$$
2 units

These values will also be used in the loop table worksheet.

The level control loop has limit alarms. Any time the level attempts to exceed 450 cm, an alarm will activate and other logic will stop the feed. Should the level fall below 300 cm, an alarm will activate and other logic will turn OFF the steam to the system. A deadband of 20 cm is provided.

- Low alarm limit

$$\frac{2.046 \text{ units}}{\text{cm}} \times 300 \text{ cm} = 613 \text{ units}$$

- High alarm limit

$$\frac{2.046 \text{ units}}{\text{cm}} \times 450 \text{ cm} = 920.7 \text{ units}$$
$$= 921 \text{ units}$$

- Alarm deadband

$$\frac{2.046 \text{ units}}{\text{cm}} \times 20 \text{ cm} = 40.92 \text{ units}$$
$$= 41 \text{ units}$$

The three loops in this example function independently and are programmed independently, each using a separate worksheet (see Tables 5-7 through 5-9). Figure 5-27 shows the program for this three-loop system.

In the loop tables, the batch unit high limit is programmed at 1023 (the maximum value in these system), and the deviation and limit alarms are programmed (even if not used). The figures given for the tuning constant are arbitrary and necessitate further adjustment, as outlined in paragraph 5-28.

Cascade control is used when a process variable can be adversely affected by another process variable. Cascading loops allows a main loop to control one or more minor loops. In the previous example, steam was used to heat a product and a single temperature control loop was used to control temperature. In that system, a variation in the flow of steam would have been corrected, but only after temperature had actually changed. An improvement in performance of the temperature control could have been brought about by using Cascade control, as shown in Figure 5-28. In the inner loop, flow is directly

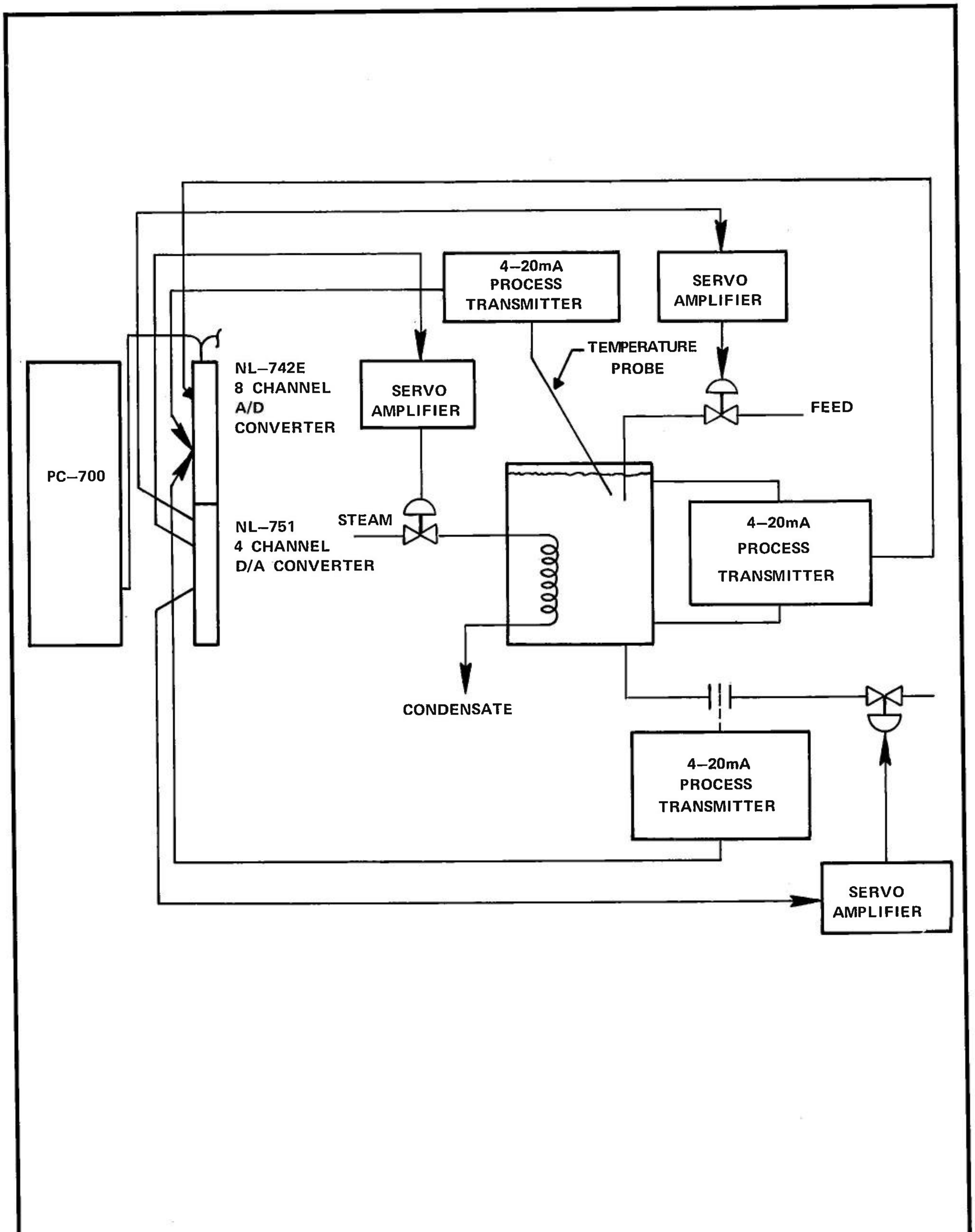


Figure 5-26. Three-Loop System — Programmable Control Configuration

TABLE 5-7. TEMPERATURE CONTROL (LT0010) DATA WORKSHEET

Loop Title: TEMPERATURE CONTROL		C V	H R	I R	O R	I G	O G	Register Type & No. (Data if CV)	Comment
	Set Point	•	•	•	•	•	•	IR0009	
	Process Variable		•	•	•	•	•	IR0001	
	Output		•		•		•	OR0001	
Loop Coil #: LT0010	Loop Table End		•					HR0032	

Loop Table Register Positions	Loop Table Actual HR Assignment	Quantity		Value/Remarks
HRXXXX-31	HR0001	Proportional Term (±32,767)	C	
HRXXXX-30	HR0002	Integral Term (±32,767)	C	
HRXXXX-29	HR0003	Derivative Term (±32,767)	C	
HRXXXX-28	HR0004	SP_n — Set Point This Sample	C	
HRXXXX-27	HR0005	PV_n — Process Variable This Sample	C	
HRXXXX-26	HR0006	Time Counter — Elapsed Sample Time	C	
HRXXXX-25	HR0007	SP_{n-1} — Set Point Previous Sample	C	
HRXXXX-24	HR0008	PV_{n-1} — Process Variable Previous Sample	C	
HRXXXX-23	HR0009	E_{n-1} — Error Previous Sample	C	
HRXXXX-22	HR0010	Bias (0 to Maximum Output)	C	
HRXXXX-21	HR0011	RESERVED		FUTURE — DO NOT USE
HRXXXX-20	HR0012	Configuration Input Word (See Below)	U	$000F_H$
HRXXXX-19	HR0013	RESERVED		FUTURE — DO NOT USE
HRXXXX-18	HR0014	RESERVED		FUTURE — DO NOT USE
HRXXXX-17	HR0015	Integral Sum (±32,767)	C	
HRXXXX-16	HR0016	E_n — Error This Sample	C	
HRXXXX-15	HR0017	T_d — Derivative Time (0 — 327.67 Min.)	U	5.00 Minutes
HRXXXX-14	HR0018	T_i — Integral Time (0 — 327.67 Min.)	U	10.00 Minutes
HRXXXX-13	HR0019	T_s — Sample Time (0 — 3276.7 Sec.)	U	100 Tenths of Seconds
HRXXXX-12	HR0020	K_c — Proportional Gain (.01 — 99.99)	U	10.00
HRXXXX-11	HR0021	Inner Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-10	HR0022	Outer Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-9	HR0023	Alarm Deadband (0 — Max PV)	U	10 Units
HRXXXX-8	HR0024	Batch Unit Preload (0 — Max Output)	U	0000 Default
HRXXXX-7	HR0025	Batch Unit Hi Limit (0 — Max Output)	U	1023 Units
HRXXXX-6	HR0026	Neg. Slew Limit (Max — ΔOutput/Sample)	U	Not Used
HRXXXX-5	HR0027	Pos. Slew Limit (Max + ΔOutput/Sample)	U	Not Used
HRXXXX-4	HR0028	Low Deviation Alarm Limit (0 — Max PV)	U	51 Units
HRXXXX-3	HR0029	High Deviation Alarm Limit (0 — Max PV)	U	102 Units
HRXXXX-2	HR0030	Low Alarm Limit (0 — Max PV)	U	0000 Default
HRXXXX-1	HR0031	High Alarm Limit (0 — Max PV)	U	1023 Units
HRXXXX	HR0032	Output Status Word	C	

C = Calculated by Processor
U = User-Entered

Configuration Input Word (HRXXXX-20)

16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

Bit Number	Definition	Status	Bit Number	Definition	Status
1	1 = Proportional Mode Selected	1	9	1 = Derivative on PV Selected 0 = Derivative on Error Selected	0
2	1 = Integral Mode Selected	1	10	1 = Batch Unit Selected	0
3	1 = Derivative Mode Selected	1	11	RESERVED FOR CONTROLLER USE	0
4	1 = Deviation Alarms Selected	1	12	0 = Anti Reset Windup When Slew Limit Occurs	0
5	1 = Error Deadband Selected	0	13	RESERVED FOR FUTURE USE	0
6	1 = Error Squared Control Selected	0	14	RESERVED FOR FUTURE USE	0
7	1 = Slew Limiting Selected	0	15	RESERVED FOR FUTURE USE	0
8	1 = Reverse Action Selected 0 = Direct Action Selected	0	16	RESERVED FOR FUTURE USE	0

TABLE 5-8. LEVEL CONTROL (LT0011) DATA WORKSHEET

Loop Title: LEVEL CONTROL		C V	H R	I R	O R	I G	O G	Register Type & No. (Data if CV)	Comment
	Set Point	•	•	•	•	•	•	HR0100	Set Point Entered Via
	Process Variable		•	•	•	•	•	IR0002	Program Loader
	Output		•		•		•	OR0002	
Loop Coil #: LT0011	Loop Table End		•					HR0064	

Loop Table Register Positions	Loop Table Actual HR Assignment	Quantity		Value/Remarks
HRXXXX-31	HR0033	Proportional Term (±32,767)	C	
HRXXXX-30	HR0034	Integral Term (±32,767)	C	
HRXXXX-29	HR0035	Derivative Term (±32,767)	C	
HRXXXX-28	HR0036	SP_n — Set Point This Sample	C	
HRXXXX-27	HR0037	PV_n — Process Variable This Sample	C	
HRXXXX-26	HR0038	Time Counter — Elapsed Sample Time	C	
HRXXXX-25	HR0039	SP_{n-1} — Set Point Previous Sample	C	
HRXXXX-24	HR0040	PV_{n-1} — Process Variable Previous Sample	C	
HRXXXX-23	HR0041	E_{n-1} — Error Previous Sample	C	
HRXXXX-22	HR0042	Bias (0 to Maximum Output)	C	
HRXXXX-21	HR0043	RESERVED		FUTURE — DO NOT USE
HRXXXX-20	HR0044	Configuration Input Word (See Below)	U	0007_H
HRXXXX-19	HR0045	RESERVED		FUTURE — DO NOT USE
HRXXXX-18	HR0046	RESERVED		FUTURE — DO NOT USE
HRXXXX-17	HR0047	Integral Sum (±32,767)	C	
HRXXXX-16	HR0048	E_n — Error This Sample	C	
HRXXXX-15	HR0049	T_d — Derivative Time (0 — 327.67 Min.)	U	5.00 Minutes
HRXXXX-14	HR0050	T_i — Integral Time (0 — 327.67 Min.)	U	10.00 Minutes
HRXXXX-13	HR0051	T_s — Sample Time (0 — 3276.7 Sec.)	U	1000 Tenths of Seconds
HRXXXX-12	HR0052	K_c — Proportional Gain (.01 — 99.99)	U	10.00
HRXXXX-11	HR0053	Inner Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-10	HR0054	Outer Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-9	HR0055	Alarm Deadband (0 — Max PV)	U	41 Units
HRXXXX-8	HR0056	Batch Unit Preload (0 — Max Output)	U	0000 Default
HRXXXX-7	HR0057	Batch Unit Hi Limit (0 — Max Output)	U	1023 Units
HRXXXX-6	HR0058	Neg. Slew Limit (Max — ΔOutput/Sample)	U	Not Used
HRXXXX-5	HR0059	Pos. Slew Limit (Max + ΔOutput/Sample)	U	Not Used
HRXXXX-4	HR0060	Low Deviation Alarm Limit (0 — Max PV)	U	Not Used
HRXXXX-3	HR0061	High Deviation Alarm Limit (0 — Max PV)	U	Not Used
HRXXXX-2	HR0062	Low Alarm Limit (0 — Max PV)	U	613 Units
HRXXXX-1	HR0063	High Alarm Limit (0 — Max PV)	U	921 Units
HRXXXX	HR0064	Output Status Word	C	

C = Calculated by Processor
U = User-Entered

Configuration Input Word (HRXXXX-20)

16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

Bit Number	Definition	Status	Bit Number	Definition	Status
1	1 = Proportional Mode Selected	1	9	1 = Derivative on PV Selected 0 = Derivative on Error Selected	0
2	1 = Integral Mode Selected	1	10	1 = Batch Unit Selected	0
3	1 = Derivative Mode Selected	1	11	RESERVED FOR CONTROLLER USE	0
4	1 = Deviation Alarms Selected	0	12	0 = Anti Reset Windup When Slew Limit Occurs	0
5	1 = Error Deadband Selected	0	13	RESERVED FOR FUTURE USE	0
6	1 = Error Squared Control Selected	0	14	RESERVED FOR FUTURE USE	0
7	1 = Slew Limiting Selected	0	15	RESERVED FOR FUTURE USE	0
8	1 = Reverse Action Selected 0 = Direct Action Selected	0	16	RESERVED FOR FUTURE USE	0

TABLE 5-9. FLOW CONTROL (LT0012) DATA WORKSHEET

Loop Title: FLOW CONTROL		C V	H R	I R	O R	I G	O G	Register Type & No. (Data if CV)	Comment
	Set Point	•	•	•	•	•	•	HR0101	Set Point Entered Via
	Process Variable		•	•	•	•	•	HR0104	Program Loader
	Output		•		•		•	OR0003	
Loop Coil #: LT0012	Loop Table End		•					HR0096	

Loop Table Register Positions	Loop Table Actual HR Assignment	Quantity		Value/Remarks
HRXXXX-31	HR0065	Proportional Term (± 32,767)	C	
HRXXXX-30	HR0066	Integral Term (± 32,767)	C	
HRXXXX-29	HR0067	Derivative Term (± 32,767)	C	
HRXXXX-28	HR0068	SP_n — Set Point This Sample	C	
HRXXXX-27	HR0069	PV_n — Process Variable This Sample	C	
HRXXXX-26	HR0070	Time Counter — Elapsed Sample Time	C	
HRXXXX-25	HR0071	SP_{n-1} — Set Point Previous Sample	C	
HRXXXX-24	HR0072	PV_{n-1} — Process Variable Previous Sample	C	
HRXXXX-23	HR0073	E_{n-1} — Error Previous Sample	C	
HRXXXX-22	HR0074	Bias (0 to Maximum Output)	C	
HRXXXX-21	HR0075	RESERVED		FUTURE — DO NOT USE
HRXXXX-20	HR0076	Configuration Input Word (See Below)	U	$000F_H$
HRXXXX-19	HR0077	RESERVED		FUTURE — DO NOT USE
HRXXXX-18	HR0078	RESERVED		FUTURE — DO NOT USE
HRXXXX-17	HR0079	Integral Sum (± 32,767)	C	
HRXXXX-16	HR0080	E_n — Error This Sample	C	
HRXXXX-15	HR0081	T_d — Derivative Time (0 — 327.67 Min.)	U	5.00 Minutes
HRXXXX-14	HR0082	T_i — Integral Time (0 — 327.67 Min.)	U	10.00 Minutes
HRXXXX-13	HR0083	T_s — Sample Time (0 — 3276.7 Sec.)	U	100 Tenths of Seconds
HRXXXX-12	HR0084	K_c — Proportional Gain (.01 — 99.99)	U	10.00
HRXXXX-11	HR0085	Inner Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-10	HR0086	Outer Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-9	HR0087	Alarm Deadband (0 — Max PV)	U	2 Units
HRXXXX-8	HR0088	Batch Unit Preload (0 — Max Output)	U	0000 Default
HRXXXX-7	HR0089	Batch Unit Hi Limit (0 — Max Output)	U	1023 Units
HRXXXX-6	HR0090	Neg. Slew Limit (Max — ΔOutput/Sample)	U	Not Used
HRXXXX-5	HR0091	Pos. Slew Limit (Max + ΔOutput/Sample)	U	Not Used
HRXXXX-4	HR0092	Low Deviation Alarm Limit (0 — Max PV)	U	6 Units
HRXXXX-3	HR0093	High Deviation Alarm Limit (0 — Max PV)	U	13 Units
HRXXXX-2	HR0094	Low Alarm Limit (0 — Max PV)	U	0000 Default
HRXXXX-1	HR0095	High Alarm Limit (0 — Max PV)	U	1023 Units
HRXXXX	HR0096	Output Status Word	C	

C = Calculated by Processor
U = User-Entered

Configuration Input Word (HRXXXX-20)

16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

Bit Number	Definition	Status	Bit Number	Definition	Status
1	1 = Proportional Mode Selected	1	9	1 = Derivative on PV Selected 0 = Derivative on Error Selected	0
2	1 = Integral Mode Selected	1	10	1 = Batch Unit Selected	0
3	1 = Derivative Mode Selected	1	11	RESERVED FOR CONTROLLER USE	0
4	1 = Deviation Alarms Selected	1	12	0 = Anti Reset Windup When Slew Limit Occurs	0
5	1 = Error Deadband Selected	0	13	RESERVED FOR FUTURE USE	0
6	1 = Error Squared Control Selected	0	14	RESERVED FOR FUTURE USE	0
7	1 = Slew Limiting Selected	0	15	RESERVED FOR FUTURE USE	0
8	1 = Reverse Action Selected 0 = Direct Action Selected	0	16	RESERVED FOR FUTURE USE	0

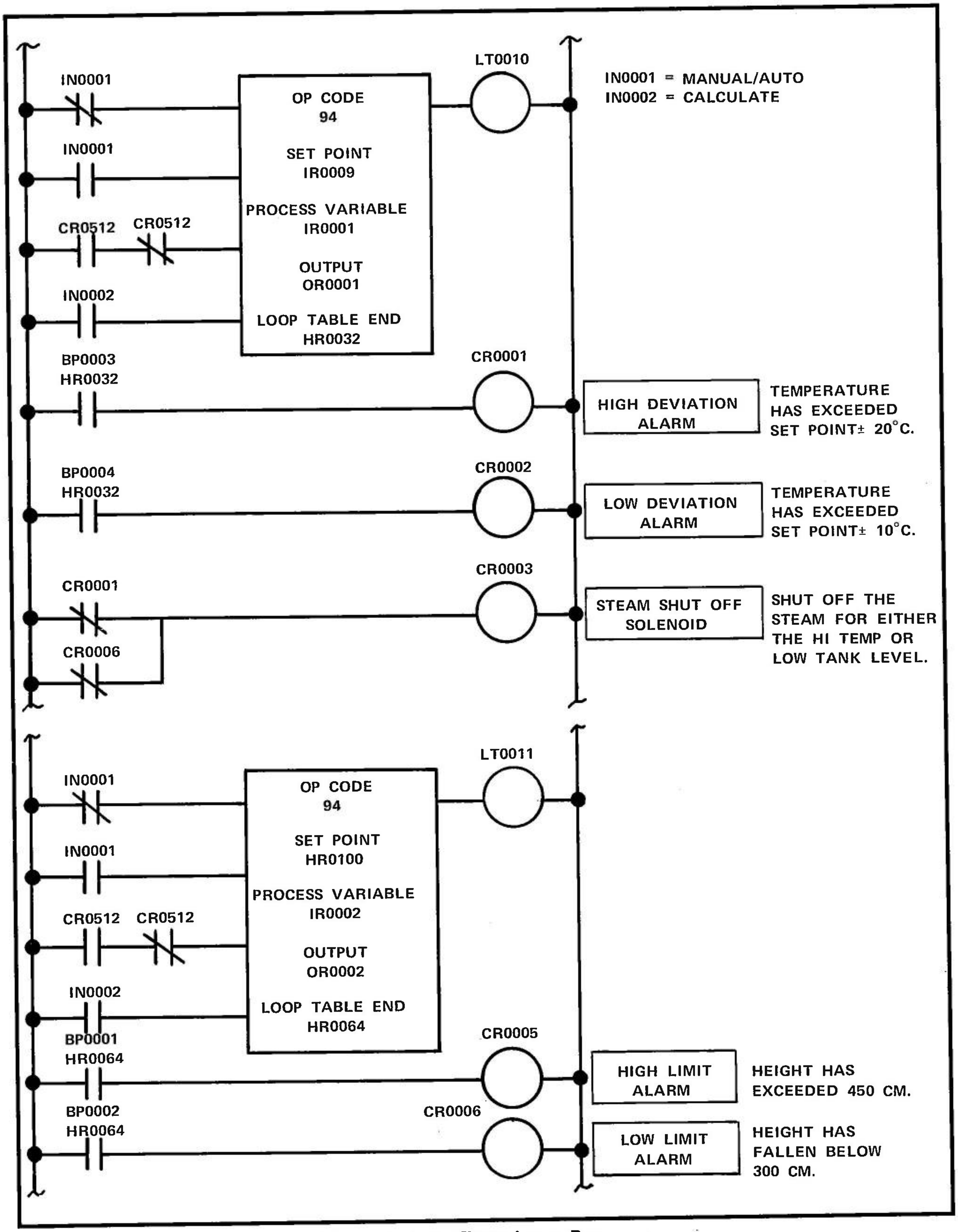


Figure 5-27a. Three-Loop Program

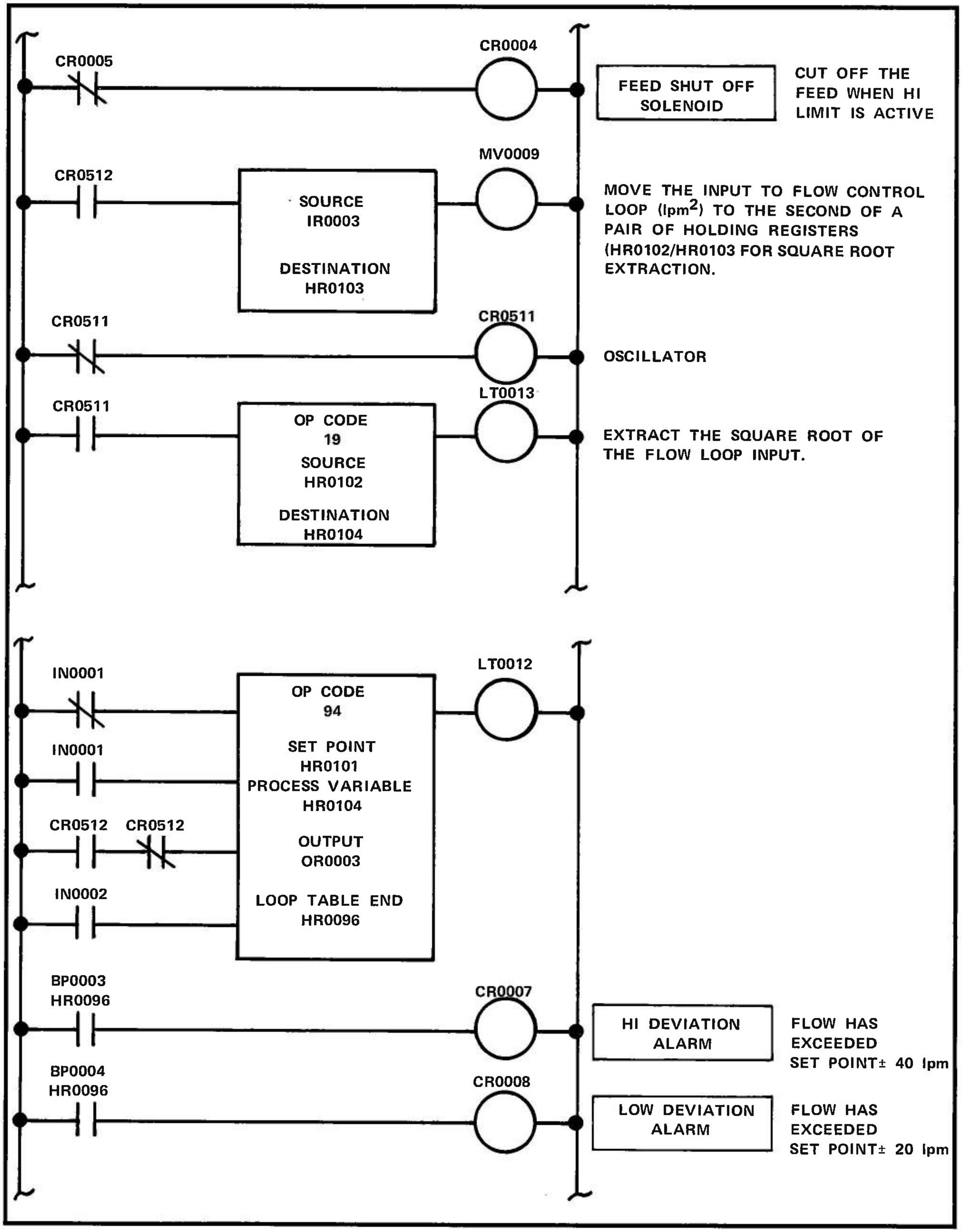


Figure 5-27b. Three-Loop Program (Cont'd)

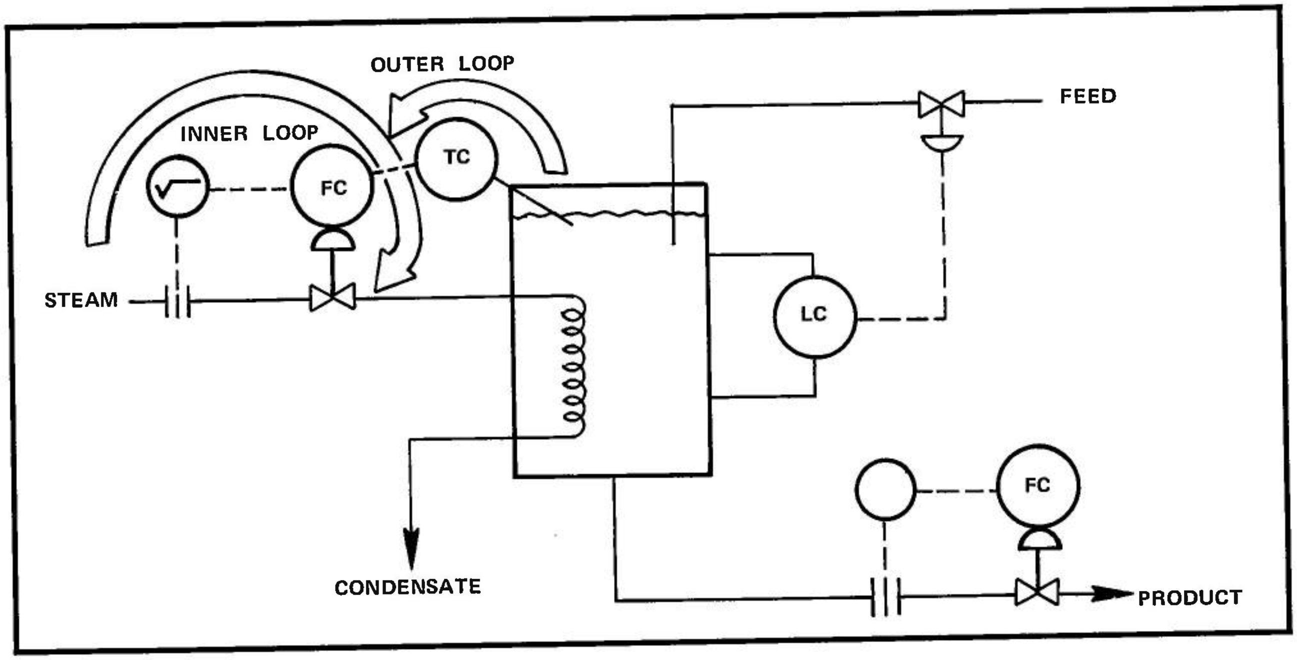


Figure 5-28. Cascade Control

controlled to a set point established by the temperature control loop output. Fluctuations in flow are dealt with directly — before they cause a change in temperature. This, in effect, removes steam flow as a variable of any consequence in this process and provides very close control of temperature.

The same control program in Figure 5-27 can be used for the level control loop and the product flow control loop; however, the temperature control loop must be modified as follows (see Figs. 5-29 and 5-30):

1. The output will be placed in a holding register location for use in programming the inner loop set point.

2. The loop table must be modified as follows:

   HR0021 = (HR)0161 inner loop pointer

The inner loop, which is a flow control loop whose process variable input is the square of flow, will require that the square root of the input be found. (See Fig. 5-30.)

Replacing LC0010 in Figure 5-27 with LC0010 through LC0013 of Figures 5-29 and 5-30 results in a Cascade control system.

The inner and outer loop pointers (table ends) must be specified in the tables for each of the loops. (See Tables 5-10 and 5-11.) When the system is configured in this manner, temperature is more closely controlled than by a simple temperature control loop.

Cascaded loops may be tuned using any of the methods described in paragraph 5-28. However, the following procedure must be followed.

1. Set both loops to Manual.
2. Load the desired outer loop set point.

TABLE 5-10. TEMPERATURE CONTROL (LT0010) — CASCADE OUTER LOOP DATA WORKSHEET

Loop Title: TEMPERATURE CONTROL		CV	HR	IR	OR	IG	OG	Register Type & No. (Data if CV)	Comment
	Set Point	•	•	•	•	•	•	IR0009	Cascade Outer Loop
	Process Variable		•	•	•	•	•	IR0001	
	Output		•		•		•	HR0102	
Loop Coil #: LT0010	Loop Table End		•					HR0032	

Loop Table Register Positions	Loop Table Actual HR Assignment	Quantity		Value/Remarks
HRXXXX-31	HR0001	Proportional Term (± 32,767)	C	
HRXXXX-30	HR0002	Integral Term (± 32,767)	C	
HRXXXX-29	HR0003	Derivative Term (± 32,767)	C	
HRXXXX-28	HR0004	SP_n — Set Point This Sample	C	
HRXXXX-27	HR0005	PV_n — Process Variable This Sample	C	
HRXXXX-26	HR0006	Time Counter — Elapsed Sample Time	C	
HRXXXX-25	HR0007	SP_{n-1} — Set Point Previous Sample	C	
HRXXXX-24	HR0008	PV_{n-1} — Process Variable Previous Sample	C	
HRXXXX-23	HR0009	E_{n-1} — Error Previous Sample	C	
HRXXXX-22	HR0010	Bias (0 to Maximum Output)	C	
HRXXXX-21	HR0011	RESERVED		FUTURE — DO NOT USE
HRXXXX-20	HR0012	Configuration Input Word (See Below)	U	$000F_H$
HRXXXX-19	HR0013	RESERVED		FUTURE — DO NOT USE
HRXXXX-18	HR0014	RESERVED		FUTURE — DO NOT USE
HRXXXX-17	HR0015	Integral Sum (± 32,767)	C	
HRXXXX-16	HR0016	E_n — Error This Sample	C	
HRXXXX-15	HR0017	T_d — Derivative Time (0 — 327.67 Min.)	U	5.00 Minutes
HRXXXX-14	HR0018	T_i — Integral Time (0 — 327.67 Min.)	U	10.00 Minutes
HRXXXX-13	HR0019	T_s — Sample Time (0 — 3276.7 Sec.)	U	100 (Tenths of Seconds)
HRXXXX-12	HR0020	K_c — Proportional Gain (.01 — 99.99)	U	10.00
HRXXXX-11	HR0021	Inner Loop Pointer (Loop Table End)	U	(HR) 0161
HRXXXX-10	HR0022	Outer Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-9	HR0023	Alarm Deadband (0 — Max PV)	U	10 Units
HRXXXX-8	HR0024	Batch Unit Preload (0 — Max Output)	U	0000 Default Valve
HRXXXX-7	HR0025	Batch Unit Hi Limit (0 — Max Output)	U	1023 Units
HRXXXX-6	HR0026	Neg. Slew Limit (Max — ΔOutput/Sample)	U	Not Used
HRXXXX-5	HR0027	Pos. Slew Limit (Max + ΔOutput/Sample)	U	Not Used
HRXXXX-4	HR0028	Low Deviation Alarm Limit (0 — Max PV)	U	51 Units
HRXXXX-3	HR0029	High Deviation Alarm Limit (0 — Max PV)	U	102 Units
HRXXXX-2	HR0030	Low Alarm Limit (0 — Max PV)	U	0000 Default
HRXXXX-1	HR0031	High Alarm Limit (0 — Max PV)	U	1023 Untis
HRXXXX	HR0032	Output Status Word	C	

C = Calculated by Processor
U = User-Entered

Configuration Input Word (HRXXXX-20)

16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

Bit Number	Definition	Status	Bit Number	Definition	Status
1	1 = Proportional Mode Selected	1	9	1 = Derivative on PV Selected 0 = Derivative on Error Selected	0
2	1 = Integral Mode Selected	1	10	1 = Batch Unit Selected	0
3	1 = Derivative Mode Selected	1	11	RESERVED FOR CONTROLLER USE	0
4	1 = Deviation Alarms Selected	1	12	0 = Anti Reset Windup When Slew Limit Occurs	0
5	1 = Error Deadband Selected	0	13	RESERVED FOR FUTURE USE	0
6	1 = Error Squared Control Selected	0	14	RESERVED FOR FUTURE USE	0
7	1 = Slew Limiting Selected	0	15	RESERVED FOR FUTURE USE	0
8	1 = Reverse Action Selected 0 = Direct Action Selected	0	16	RESERVED FOR FUTURE USE	0

TABLE 5-11. FLOW CONTROL (LT0013) — CASCADE INNER LOOP DATA WORKSHEET

Loop Title: FLOW CONTROL		C V	H R	I R	O R	I G	O G	Register Type & No. (Data if CV)	Comment
	Set Point	•	•	•	•	•	•	HR0102	Cascade Inner Loop
	Process Variable		•	•	•	•	•	HR0108	
	Output		•		•		•	OR0001	
Loop Coil #: LT0013	Loop Table End		•					HR0161	

Loop Table Register Positions	Loop Table Actual HR Assignment	Quantity		Value/Remarks
HRXXXX-31	HR0130	Proportional Term (±32,767)	C	
HRXXXX-30	HR0131	Integral Term (±32,767)	C	
HRXXXX-29	HR0132	Derivative Term (±32,767)	C	
HRXXXX-28	HR0133	SP_n — Set Point This Sample	C	
HRXXXX-27	HR0134	PV_n — Process Variable This Sample	C	
HRXXXX-26	HR0135	Time Counter — Elapsed Sample Time	C	
HRXXXX-25	HR0136	SP_{n-1} — Set Point Previous Sample	C	
HRXXXX-24	HR0137	PV_{n-1} — Process Variable Previous Sample	C	
HRXXXX-23	HR0138	E_{n-1} — Error Previous Sample	C	
HRXXXX-22	HR0139	Bias (0 to Maximum Output)	C	
HRXXXX-21	HR0140	RESERVED		FUTURE — DO NOT USE
HRXXXX-20	HR0141	Configuration Input Word (See Below)	U	0007_H
HRXXXX-19	HR0142	RESERVED		FUTURE — DO NOT USE
HRXXXX-18	HR0143	RESERVED		FUTURE — DO NOT USE
HRXXXX-17	HR0144	Integral Sum (±32,767)	C	
HRXXXX-16	HR0145	E_n — Error This Sample	C	
HRXXXX-15	HR0146	T_d — Derivative Time (0 — 327.67 Min.)	U	5.00 Minutes
HRXXXX-14	HR0147	T_i — Integral Time (0 — 327.67 Min.)	U	10.00 Minutes
HRXXXX-13	HR0148	T_s — Sample Time (0 — 3276.7 Sec.)	U	100 Tenths of Seconds
HRXXXX-12	HR0149	K_c — Proportional Gain (.01 — 99.99)	U	5.00
HRXXXX-11	HR0150	Inner Loop Pointer (Loop Table End)	U	Not Used
HRXXXX-10	HR0151	Outer Loop Pointer (Loop Table End)	U	(HR) 0032
HRXXXX-9	HR0152	Alarm Deadband (0 — Max PV)	U	Not Used
HRXXXX-8	HR0153	Batch Unit Preload (0 — Max Output)	U	0000 Default
HRXXXX-7	HR0154	Batch Unit Hi Limit (0 — Max Output)	U	4095 Default
HRXXXX-6	HR0155	Neg. Slew Limit (Max — ΔOutput/Sample)	U	Not Used
HRXXXX-5	HR0156	Pos. Slew Limit (Max + ΔOutput/Sample)	U	Not Used
HRXXXX-4	HR0157	Low Deviation Alarm Limit (0 — Max PV)	U	0000
HRXXXX-3	HR0158	High Deviation Alarm Limit (0 — Max PV)	U	4095
HRXXXX-2	HR0159	Low Alarm Limit (0 — Max PV)	U	0000 Default
HRXXXX-1	HR0160	High Alarm Limit (0 — Max PV)	U	4095 Default
HRXXXX	HR0161	Output Status Word	C	

C = Calculated by Processor
U = User-Entered

Configuration Input Word (HRXXXX-20)

16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

Bit Number	Definition	Status	Bit Number	Definition	Status
1	1 = Proportional Mode Selected	1	9	1 = Derivative on PV Selected 0 = Derivative on Error Selected	0
2	1 = Integral Mode Selected	1	10	1 = Batch Unit Selected	0
3	1 = Derivative Mode Selected	1	11	RESERVED FOR CONTROLLER USE	0
4	1 = Deviation Alarms Selected	0	12	0 = Anti Reset Windup When Slew Limit Occurs	0
5	1 = Error Deadband Selected	0	13	RESERVED FOR FUTURE USE	0
6	1 = Error Squared Control Selected	0	14	RESERVED FOR FUTURE USE	0
7	1 = Slew Limiting Selected	0	15	RESERVED FOR FUTURE USE	0
8	1 = Reverse Action Selected 0 = Direct Action Selected	0	16	RESERVED FOR FUTURE USE	0

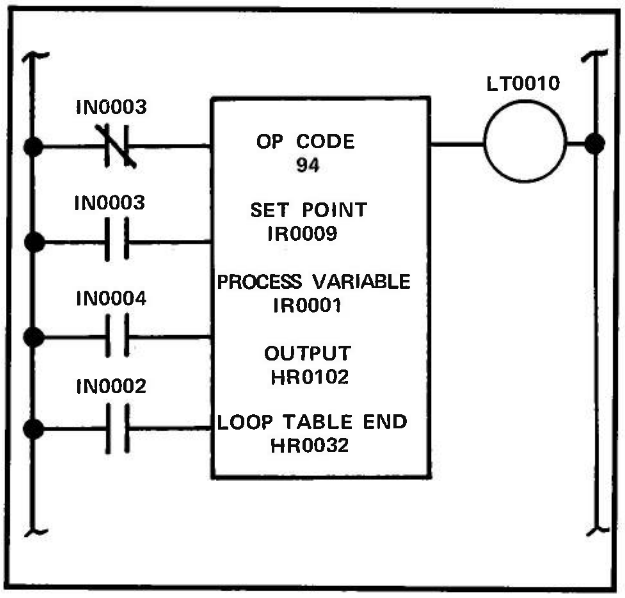


Figure 5-29. Cascade Program: LC

3. Adjust the inner loop output until the set point equals the process variable on the output loop.

4. Adjust the set point of the inner loop until the set point equals the process variable on the inner loop.

5. Place the inner loop in Auto. This sets the bias of the inner loop equal to the output of the inner loop and zeroes the integral term and error.

6. Put the inner loop in Cascade. This transfers the output of the outer loop to the set point of the inner loop.

7. Put the outer loop in Auto. This sets the bias of the outer loop equal to the output of the outer loop and zeroes the integral term and error.

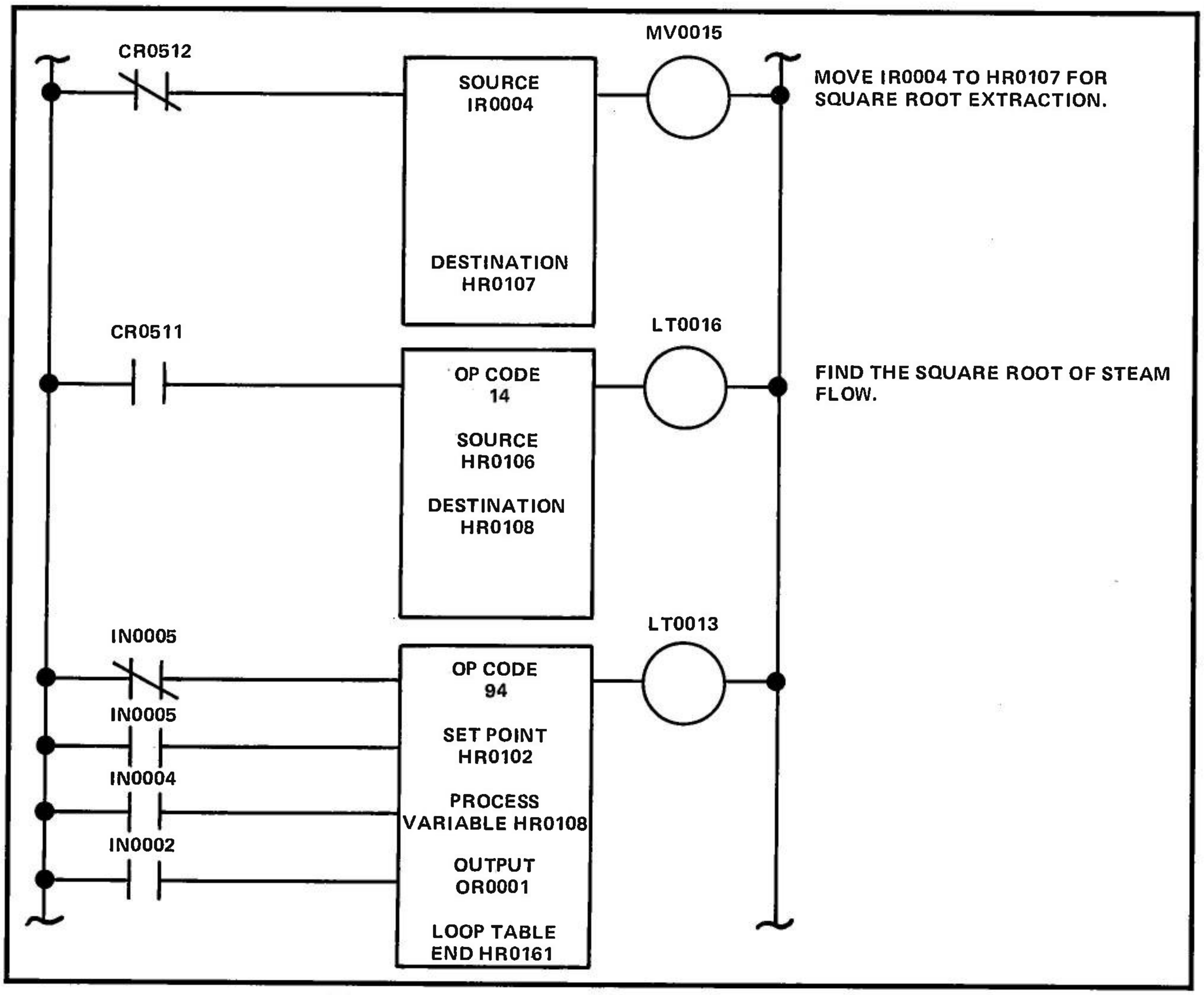


Figure 5-30. Cascade Program: Square Root

5-28. LOOP TUNING METHODS

The LC function operates by using a form of the PID control equation:

$$M - M_o = K_c \left[e + \frac{T_s}{T_i}\int edt + \left(\frac{T_d}{T_s}\frac{de}{dt}\right)\right]$$

where:

M = Controller

M_o = Bias

K_c = Gain

e = Error (actual vs. desired)

T_i = Integral time

T_d = Derivative time

T_s = Sample time

Three of these parameters must be established by the user: K_c, T_i and T_d. In addition, a fourth quantity, T_s, must be established. The development of these quantities is called "tuning the loop". To date, there are no foolproof methods of establishing these parameters at the loop design state. Many control loops are, in fact, started and brought to optimum operating conditions, and then tuned.

There are two basic approaches to loop tuning:

1. Establish and enter the appropriate values. Observe the performance; then, modify the settings.
2. Use a tuning technique involving a process test to obtain data from which settings can be determined. Most often, the first technique is used, but this technique may be more valuable in critical processes.

When using the first method, a systematic approach will yield faster, better results:

1. Delete the Integral and Derivative modes by setting the I and D bits in the Configuration Input Word to zero; this leaves only the Proportional mode. Put the controller in Manual; adjust the output until the desired process variable is achieved. Switch to Auto. (The controller stores the output in a bias register, and zeroes the P, I and D terms, along with e.) Adjust the proportional gain, K_c, for desired behavior (start with 1.00 through 5.00; adjust for a better response).
2. If the derivative is to be used, activate the Derivative mode by setting the D bit in the Configuration Input Word to 1. Adjust T_d and, if necessary, readjust K_c.
3. If the integral is to be used, activate it in the Configuration Input Word and adjust T_i for the desired operation. It should not be necessary to adjust either K_c or T_d.

5-29. Proportional Gain (K_c)

With the integral and derivative control removed, only K_c must be adjusted. The following procedure may be helpful:

1. Ensure that the I and D bits of the Configuration/Input Word are set to zero.
2. Allow the process to stablize (line out) at the desired operation condition.
3. Place the loop into Auto.
4. Quickly move up the set point (i.e., introduce a step change).
5. Observe the system response and adjust for proper response as shown in Figure 5-31.
6. Return the set point to the original setting and observe the response. Figure 5-31 can be used.
7. Continue the step changes until the loop is adjusted as desired.

Note

The higher the gain, the smaller the offset; the lower the gain, the larger the offset.

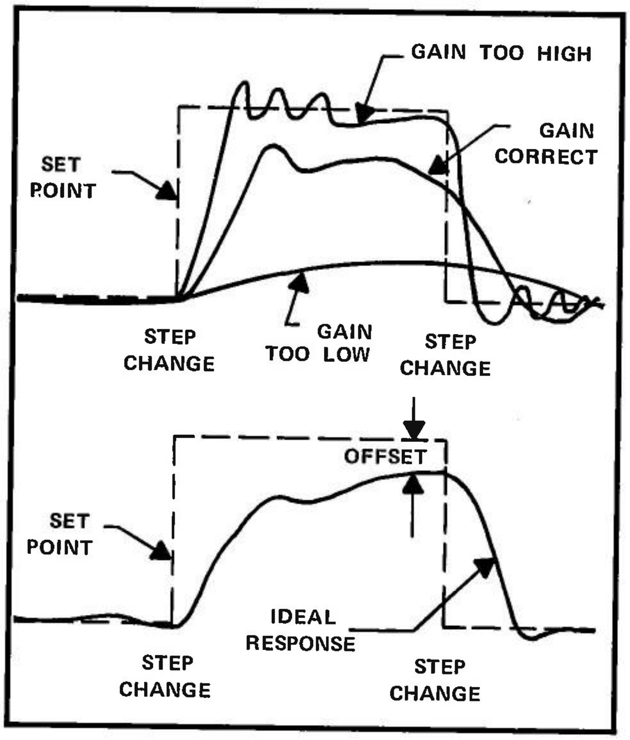


Figure 5-31. Effects of Proportional Gain

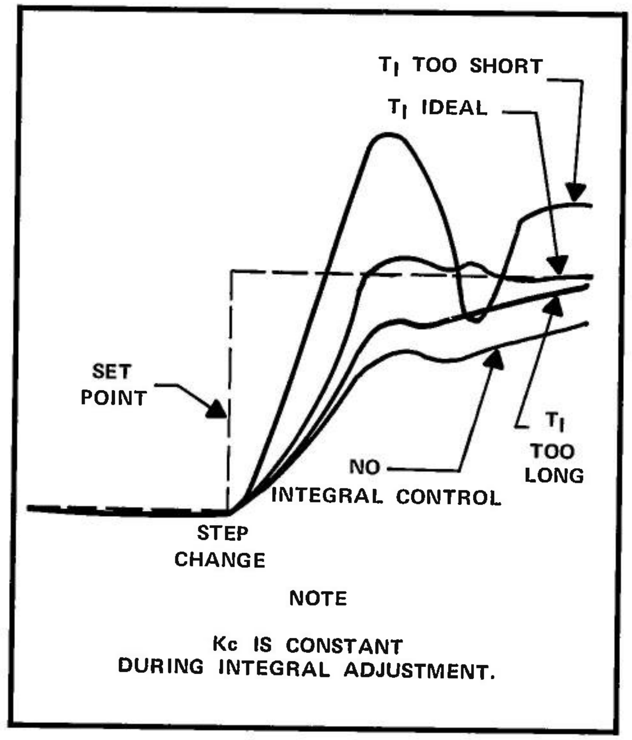


Figure 5-32. PI Response

5-30. Integral (Reset) Time (T_i)

If the controller is to operate without offset, some integral action can be introduced. The ability of a PI loop to operate without offset makes it the most popular form of the control. To adjust T_i, the following steps can be followed (see Fig. 5-32):

1. Adjust the proportional gain as discussed previously.
2. Activate the Integral control mode by setting the appropriate bit in the Configuration Input Word to 1.
3. Adjust T_i until the desired operation is achieved.

5-31. Derivative (Rate) Control

Almost all process loops can benefit from derivative (rate) control, but it is most difficult to properly adjust. There are at least two cases where derivative control is not beneficial:

1. When the process variable is noisy. (Noise induces a false response.)
2. When the process has a large deadtime/transport lag (over the response of the controller).

Other cases can be found that are not benefited by derivative (rate) control; these are beyond the scope of this document. The following procedure is suggested for derivative adjustment.

1. Adjust K_c with the Integral (Reset) mode deactivated.
2. Activate and adjust T_d. This may result in the need to increase K_c.
3. Activate and adjust T_i.

Note

Too much derivative control will cause oscillation.

The effects of derivative action are shown in Figure 5-33.

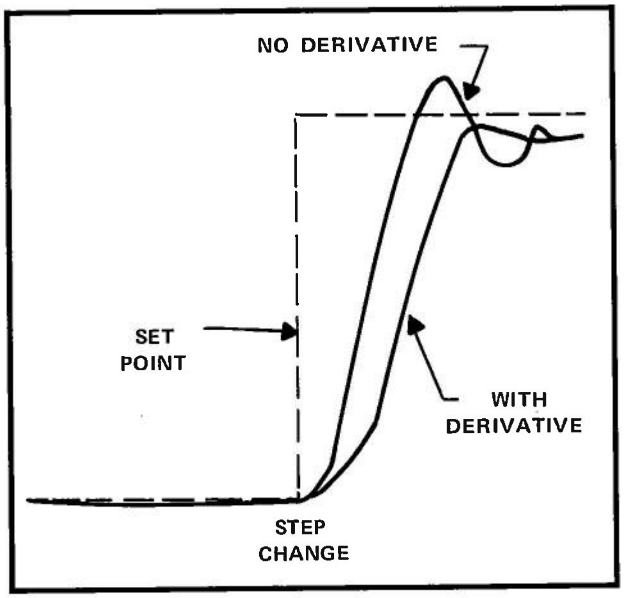


Figure 5-33. Effects of Derivative Action

5-32. TUNING TECHNIQUES

The following tuning technique attempts to avoid the many step changes involved in Manual tuning. A process test is used that provides data from which initial settings can be calculated. The test procedure is:

1. Line out the process.
2. Place the controller in Manual.
3. Change the output (up or down) by approximately 10 percent of its range, and level it at the new setting. Record the old and new settings.
4. Record the response of the process variable.

The result of this test is a process reaction curve. (See Figure 5-34). A good quality recorder is required; effort should be made to prevent outside disturbances to the process during testing.

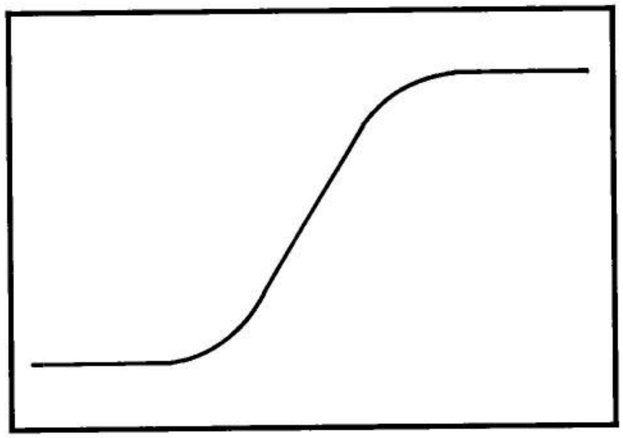


Figure 5-34. Typical Process Reaction Curve

The Ziegler-Nichols tuning procedure requires that two parameters be developed from this curve:

- Lr (Reaction lag)
- Rr (Reaction rate)

These parameters are determined graphically, as shown in Figure 5-35.

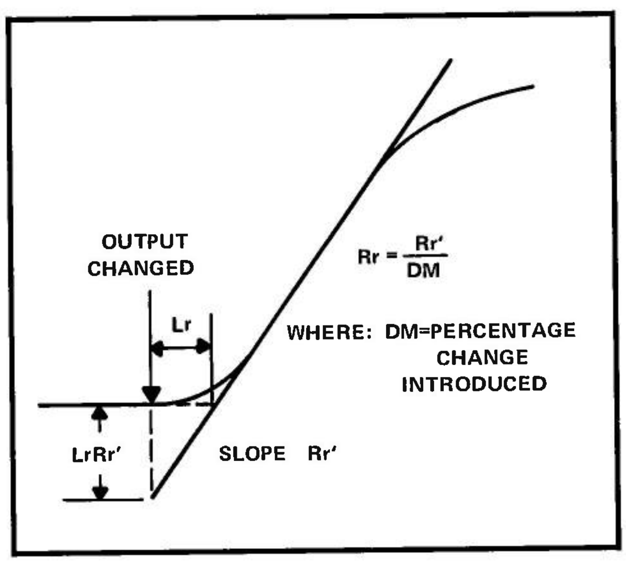


Figure 5-35. Calculations Using Process Reaction Curve

The following can be calculated by using the quantities determined graphically from Figure 5-34.

- Proportional gain (for proportional controllers)

  $$K_c = \frac{1}{LrRr}$$

- PI (for PI controllers)

  $$K_c = \frac{0.9}{LrRr}$$

  $$T_i = 3.33Lr$$

- PID (for PID controllers)

  $$K_c = \frac{1.2}{LrRr}$$

  $$T_i = 2.0\ Lr$$

  $$T_d = 0.5\ Lr$$

Although this method is somewhat crude, it yields usable results. Using such a method provides "ball park" initial settings and may reduce the number of further adjustments that must be made.

Loop tuning by any method requires an intimate knowledge of the process under control. The resultant system operation is determined by the process under control, the control system used, and the person tuning the loop.

The guidelines included in this section provide a starting point from which the user can develop the tuning method best suited to system requirements.

Loop Title:		CV	HR	IR	OR	IG	OG	Register Type & No. (Data if CV)	Comment
	Set Point	•	•	•	•	•	•		
	Process Variable		•	•	•	•	•		
	Output		•		•		•		
Loop Coil #:	Loop Table End		•						

Loop Table Register Positions	Loop Table Actual HR Assignment	Quantity		Value/Remarks
HRXXXX-31		Proportional Term (± 32,767)	C	
HRXXXX-30		Integral Term (± 32,767)	C	
HRXXXX-29		Derivative Term (± 32,767)	C	
HRXXXX-28		SP_n — Set Point This Sample	C	
HRXXXX-27		PV_n — Process Variable This Sample	C	
HRXXXX-26		Time Counter — Elapsed Sample Time	C	
HRXXXX-25		SP_{n-1} — Set Point Previous Sample	C	
HRXXXX-24		PV_{n-1} — Process Variable Previous Sample	C	
HRXXXX-23		E_{n-1} — Error Previous Sample	C	
HRXXXX-22		Bias (0 to Maximum Output)	C	
HRXXXX-21		RESERVED		FUTURE — DO NOT USE
HRXXXX-20		Configuration Input Word (See Below)	U	
HRXXXX-19		RESERVED		FUTURE — DO NOT USE
HRXXXX-18		RESERVED		FUTURE — DO NOT USE
HRXXXX-17		Integral Sum (± 32,767)	C	
HRXXXX-16		E_n — Error This Sample	C	
HRXXXX-15		T_d — Derivative Time (0 — 327.67 Min.)	U	
HRXXXX-14		T_i — Integral Time (0 — 327.67 Min.)	U	
HRXXXX-13		T_s — Sample Time (0 — 3276.7 Sec.)	U	
HRXXXX-12		K_c — Proportional Gain (.01 — 99.99)	U	
HRXXXX-11		Inner Loop Pointer (Loop Table End)	U	
HRXXXX-10		Outer Loop Pointer (Loop Table End)	U	
HRXXXX-9		Alarm Deadband (0 — Max PV)	U	
HRXXXX-8		Batch Unit Preload (0 — Max Output)	U	
HRXXXX-7		Batch Unit Hi Limit (0 — Max Output)	U	
HRXXXX-6		Neg. Slew Limit (Max — ΔOutput/Sample)	U	
HRXXXX-5		Pos. Slew Limit (Max + ΔOutput/Sample)	U	
HRXXXX-4		Low Deviation Alarm Limit (0 — Max PV)	U	
HRXXXX-3		High Deviation Alarm Limit (0 — Max PV)	U	
HRXXXX-2		Low Alarm Limit (0 — Max PV)	U	
HRXXXX-1		High Alarm Limit (0 — Max PV)	U	
HRXXXX		Output Status Word	C	

C = Calculated by Processor
U = User-Entered

Configuration Input Word (HRXXXX-20)

16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1

Bit Number	Definition	Status	Bit Number	Definition	Status
1	1 = Proportional Mode Selected		9	1 = Derivative on PV Selected 0 = Derivative on Error Selected	
2	1 = Integral Mode Selected		10	1 = Batch Unit Selected	
3	1 = Derivative Mode Selected		11	RESERVED FOR CONTROLLER USE	
4	1 = Deviation Alarms Selected		12	0 = Anti Reset Windup When Slew Limit Occurs	
5	1 = Error Deadband Selected		13	RESERVED FOR FUTURE USE	
6	1 = Error Squared Control Selected		14	RESERVED FOR FUTURE USE	
7	1 = Slew Limiting Selected		15	RESERVED FOR FUTURE USE	
8	1 = Reverse Action Selected 0 = Direct Action Selected		16	RESERVED FOR FUTURE USE	