Logic Control Systems

To begin the discussion of industrial logic control systems, consider the simple pneumatic system shown in Figure LC-1. The pneumatic cylinder moves in a linear dimension until it reaches the limit switch at the extended end. The cylinder is controlled with a simple two position, four-way solenoid valve as shown. The solenoid valve shown is activated by an electrical current passing through the solenoid coil. This type of simple ON/OFF programming has traditionally been done by relay control systems.

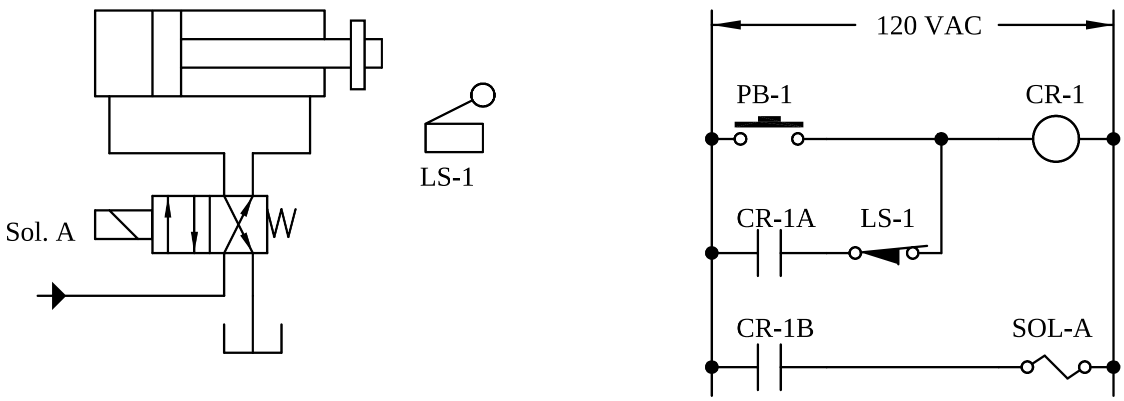


Figure LC-1: Simple pneumatic and logic control system

A relay control system for the simple system of Figure LC-1 is also shown. This schematic diagram represents a type of programming frequently referred to as "ladder logic" by industrial electricians. The two parts of a relay are both shown in this diagram. Electrical relays (Figure LC-2) have a control circuit and one or more sets of outputs. The coil of the relay forms part of an electromagnet which activates a set of contacts (contacts similar to "points" in an pre-70's auto). Electrical current passing through the coil of the relay (the "control relay") closes one of these sets of contacts (CR-1B) which allows current to flow through the pneumatic valve solenoid, SOL-A. Another set of contacts, CR-1A in Figure LC-1, is used to "hold" the contacts closed once they have been energized, by providing an alternate path for electrical current through the control relay. A momentary contact push-button PB-1 (normally open or N.O.) is provided for initiating motion. When PB-1 is pressed, current flows through the actuating circuit of relay CR-1, which closes the output contacts (CR-1A and CR-1B). When PB-1 is released, these contacts remain closed due to electrical current path through the closed relay contacts CR-1A and the normally closed limit switch LS-1. Relay CR-1 remains energized until the limit switch LS-1 activated by the cylinder. Once

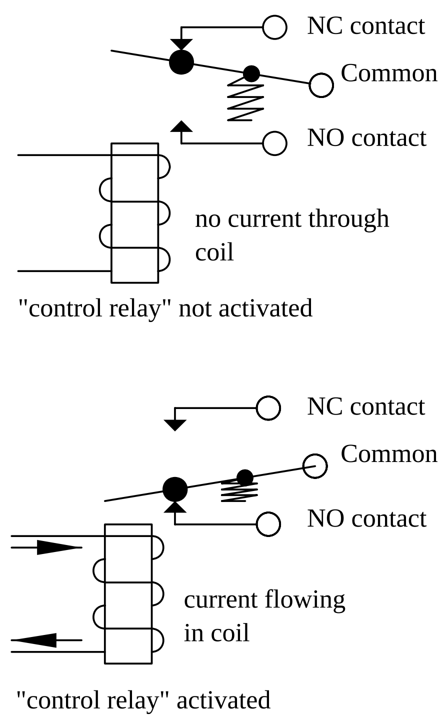


Figure LC-2: Control relay with NO and NC contacts this limit switch is activated, the current flow through the control relay CR-1 is interrupted, and the contacts CR-1A and CR-1B both open. The solenoid SOL-A is de-energized, therefore the spring shifts the solenoid back to the right position, which causes the cylinder to retract. The circuit is inactive until a subsequent pressing of the push-button PB-1.

Figure LC-3 shows the most common components of ladder logic diagrams. Input elements include limit switches, momentary contact push-buttons, pressure switches, manual switches, and relay contacts. Typical outputs include solenoid coils, control relay coils, pilot lights, and annunciators (or horns). Note that each of the inputs is available in both normally open (NO) and normally closed (NC) configurations. This distinction is easily explained by observing the limit switch configurations. A normally closed limit switch will carry current if it is not activated (the "normal" state). If a normally closed limit switch is pressed, then it no longer will carry current. A normally open limit switch is the opposite - it will not carry current inactivated, it must be pressed to allow current to flow through it.

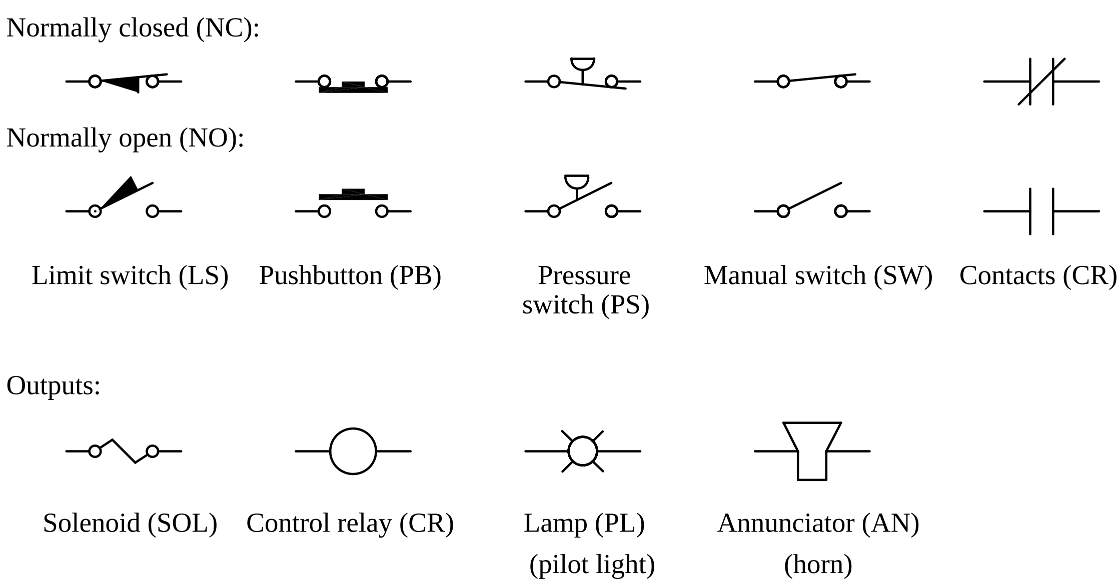
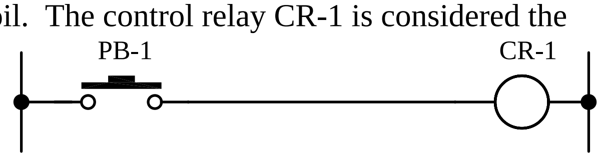


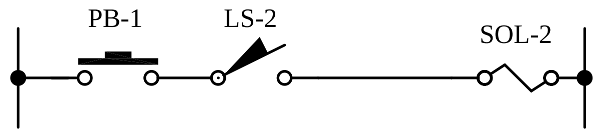
Figure LC-3: Ladder logic schematic elements

Several simple ladder logic diagrams are given below to illustrate the use of ladder logic. In each of these diagrams an "equivalent" BASIC statement is also given for comparison (all variables considered to be logical variables). In the first diagram, a single momentary contact push-button activates a control relay coil. The control relay CR-1 is considered the output and the momentary contact pushbutton PB-1 is the input. Note that the coil is activated only while the push-button is held down, once it is released the coil is no longer activated.



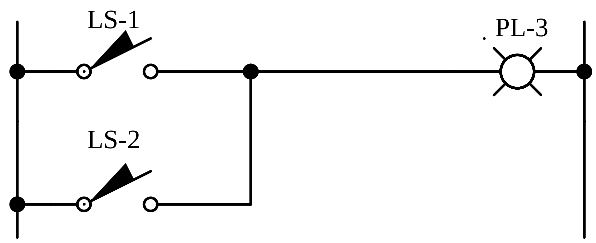
CR-1 = PB-1

In the next example a logical "AND" configuration is implemented. Two inputs (PB-1 and LS-2) are used to activate a single output (SOL-2). In order to activate the output, both of the input must be activated <u>at the same time</u>. Once the push-button PB-1 is released or the limit switch LS-1 is not activated, the solenoid coil SOL-2 is no longer active.



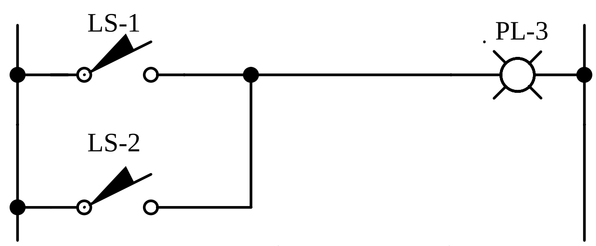
SOL-2 = (PB-1 and LS-2)

A logical "OR" configuration is shown in this diagram. If either of the two inputs (LS-1 or LS-2) is activated, or both of them, then the output pilot light PL-3 will come on. If neither inputs is activated, then the output PL-3 will be off. Note that two alternate paths for electrical current are provided through the two limit switches.



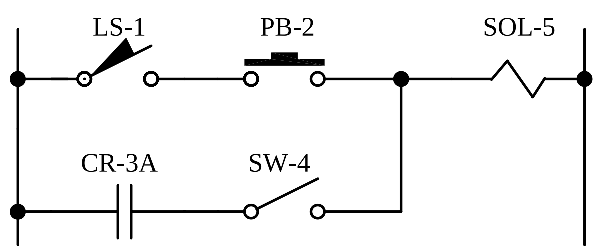
PL-3 = (LS-1 or LS-2)

A combination of logical "AND" and "OR" is given in this example. The contacts CR-3A must be closed <u>and</u> at least one of the other two inputs (LS-1 and PS-2) must be activated.
Note that the CR-3A contacts are closed by activating the control relay CR-3 on another rung of the ladder diagram. Contacts associated with CR-3 can appear many times on the ladder diagram, but the control relay itself can appear as an output on only one rung.



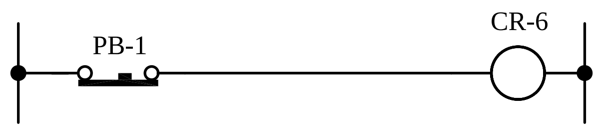
PL-3 = (LS-1 or LS-2)

Another combination of logical "AND": and logical "OR" elements is given in this example. There are two ways to activate the output SOL-5, activate LS-1 <u>and</u> PB-2 simultaneously, <u>or</u> activate contacts CR-3A <u>and</u> switch SW-4 simultaneously. Momentary contact push-buttons are much more common than switches (like SW-4), due to safety considerations. Again, note the two alternate paths for current to flow from the left to the right sides of the "ladder."



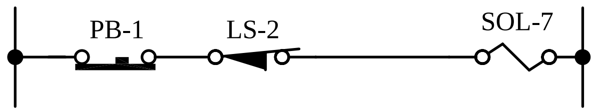
SOL-5 = (LS-1 and PB-2) or (CR-3A and SW-4)

The following examples show the use of normally closed contacts. In the first example, the control relay coil CR-6 is activated as long as the push-button PB-1 is <u>not</u> pressed. Pressing PB-1 will deactivate the coil CR-6.



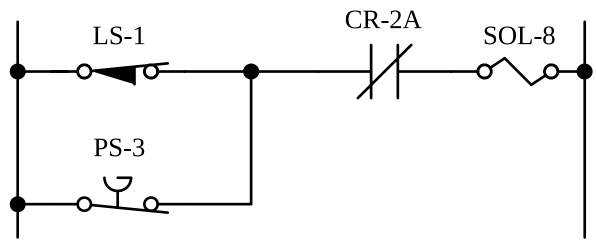
CR-6 = (not PB-1)

A logical "AND" function is shown in this example along with normally closed elements. As long as neither of the inputs (PB-1 and LS-2) is activated, the output solenoid coil SOL-7 will be activated. If either input is activated, then the output solenoid is de-energized.



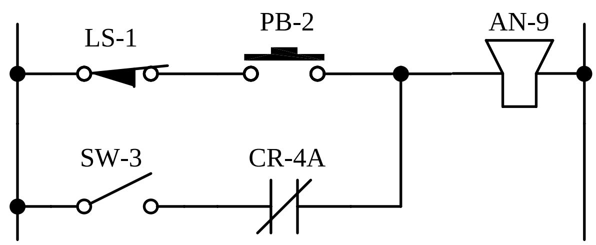
SOL-7 = (not PB-1) and (not LS-2)

A combination "AND" and "OR" rung is shown with normally closed elements. The output solenoid SOL-8 will be activated as long as CR-2 is not activated and either LS-1 or PS-3 is not activated. Note that the normally closed contacts CR-2A remain closed until the control relay coil CR-2 is activated on another rung of the ladder diagram. Normally closed contacts (like CR-2A) can occur as many times as needed in the ladder diagram.



SOL-8 = ((not LS-1) or (not PS-3)) and (not CR-2A)

The final example shows a logical "AND" and "OR" combination with both normally open and normally closed elements. The output horn AN-9 will be activated if either (or both) of the following conditions is satisfied: input LS-1 is not activated <u>and</u> push-button PB-1 is, <u>or</u> switch SW-3 is activated <u>and</u> control relay CR-4 is not activated.



AN-9 = ((not LS-1) and PB-2) or
(SW-3 and (not CR-4A))

Programmable Controllers

One of the disadvantages of the relay logic systems of the previous section is the difficult nature of the "programming." The program logic is "hard-wired" by the interconnection of the relays, limit switches, timers, counters, etc. Changing the task performed by the simple system of Figure LC-1 requires physically moving the wires from the relays and limit switches and placing them in the desired new configuration. For circuits with only three or four components this is not difficult. However, systems containing ten to several hundred individual components are not uncommon in industrial automation systems.

The programmable logic controller (PLC) was developed in the early 60's to overcome the deficiencies of relay logic systems. Programmable logic is implemented using a microcomputer instead of the hard-wired logic of the conventional hard-wired relay system. The major advantage of PLC's (frequently referred to as just programmable controllers or PC's) is that the programming can be done in ladder logic, just like relay logic systems. Electricians and technicians can readily adapt to this familiar type of programming. A computer language like BASIC or Pascal might be too intimidating and is not required to implement straightforward machine logic.

The major criteria for specifying PLC's are the number of input contacts that can be read and the number of output switches that can be controlled. Small PLC's might have 8 to 12 inputs and outputs, while larger models can use 100 or more I/O (input/ output) points. Inputs are usually 0-120 volts AC or 0-24 volts DC. Output options frequently include relay contacts, triac (120 VAC) or 24 volt (open collector). Some of the newer PLC models have such advanced features as analog inputs (0 - 10 Volts), PID (proportional- integral-derivative) control loops, and serial (RS-232) communications capabilities.

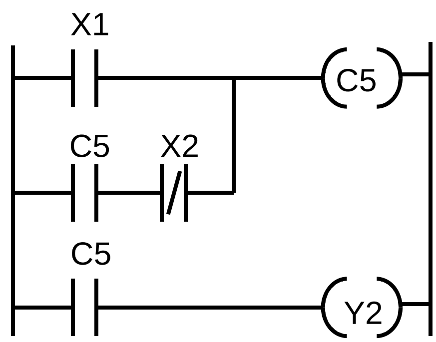


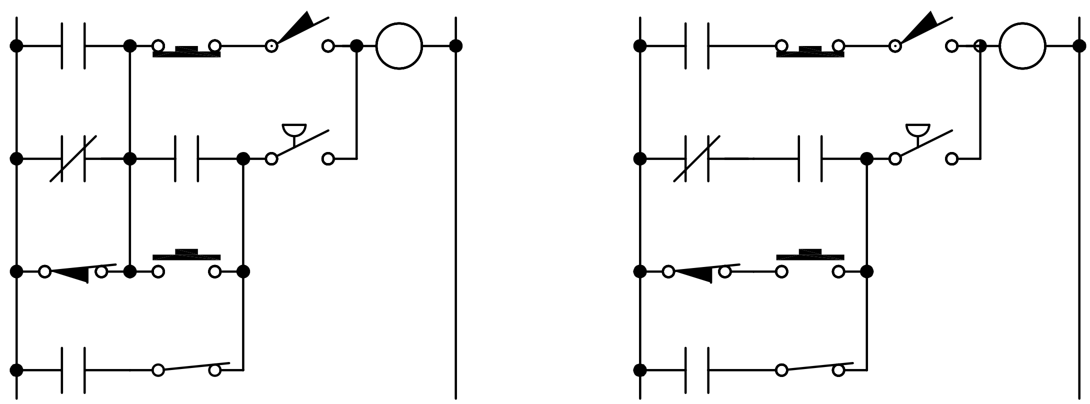
Figure LC-4: PLC ladder diagram

Figure LC-4 shows a programmable controller ladder diagram for the same simple system of Figure LC-1. The "internal" contact labeled X1 is connected to the input push-button, PB-1. The normally open limit switch, LS-1, is wired to the input contact X2. The internal contact C5 replaces the control relay CR-1 and its two pairs of contacts. The output solenoid coil, SOL-A, is connected to the output contact Y2. By comparing this figure to the relay system of Figure LC-1, the similarities between PLC programming and relay logic is obvious. One simplifying difference is that internal registers (such as X1, X2, and C5) can be used as replacements for inputs and control relay circuits. An essentially unlimited number of input contacts and control relay contacts are therefore available, although the number of actual input devices is limited. A finite number of actual outputs (such as Y2) are available, but their status can be read as many times as needed on other rungs of the ladder. Also, counters and timers are readily programmed on even the simplest PLC's.

In ME 360 we will use a combination of conventional hard-wired relay and PLC logic programming techniques. Rules for drawing ladder logic diagrams are summarized below:

1) Ladder diagrams are drawn vertically with inputs on the left and outputs on the right.
2) Each rung of the ladder has one (and only one) output.
3) An individual output device can appear on the ladder diagram only once.
4) An individual physical input device (limit switch, push-button, pressure switch, etc.) may be used as many times as necessary on the ladder diagram in both normally open and normally closed configurations, and is drawn using the schematic symbol of Figure LC-3.
5) Internal contacts of the PLC are represented as conventional control relays and contacts.
6) Control relay coils are outputs and can appear on the ladder diagram only once.
7) Control relay contacts are inputs and may be used as many times as necessary on the ladder diagram in both normally open and normally closed configurations.
8) Unlimited "OR"ing of ladder rungs is allowed, but any rung of the ladder diagram may be "OR"ed with a following rung at only one location.

Hard-wired logic systems are drawn in both horizontal and vertical configurations, but PLC diagrams are conventionally drawn vertically with single outputs in the rightmost column. If an output appeared at more than one location, then its status could be ambiguous. Physical input devices (limit switches, push-buttons, pressure switches, etc.) and relays have a limited number of normally open and/or normally closed contacts. Hard-wired logic systems can use only as many of these inputs or contacts as are physically available. PLC circuits allow unlimited use of their internal contacts which may also be connected to input devices. Contacts are normally shown for all inputs in a PLC diagram (as shown in Figure LC-4), but we will use the schematic symbols of Figure LC-3 for clarity. Nested "OR" networks shown on the left in Figure LC-5 are allowed in hard-wired relay logic systems, but are not in PLC's. Note that the first and second rungs are "OR"ed at two locations, as are the second and third rungs. The "OR" configuration shown on the right in Figure LC-5 is allowed in a PLC system (see Rule #8 above). Note that the order of the rungs on the right is irrelevant, the rungs are drawn in order of fewer components for clarity.



Invalid "OR" connections

Valid "OR" connections

Figure LC-5: Nested "OR" programming

Logic Control Circuit Design

Designing new logic control circuits from "scratch" can be a daunting task. Oftentimes a designer can reuse logical blocks from previous successful designs. Unfortunately, this is not always possible, and can sometimes lead to unforseen interactions between various parts of the logic system. Some broad general guidelines (which are often violated!) for designing logic systems are given below:

1. Dedicate control relays for specific functions (such as starting the system, activating a solenoid, etc.) and use as many as are necessary. Control relays are essentially "free" once a programmable controller has been purchased, so don't be miserly!
2. Control relays almost always use a holding circuit, so design in terms of both a "turn ON" and a "turn OFF" rung with an "OR" connection between them. Note that some circuits will require multiple rungs for turning ON or OFF, which must be connected through the OR structure.
3. Normally open (N.O.) components are <u>usually</u> used to activate the "turn ON" rung.
4. Normally closed (N.C.) components are <u>usually</u> used to activate the "turn OFF" rung.
5. Be absolutely certain that any holding circuit formed will be actively turned off by your system. Do not depend on a power shutdown to release and holding circuits.
6. Provide safety interlocks either on the "turn ON" rung before the control relay or on the associated solenoid activation rung, depending on the type of interlock required.
7. Use the master control relay (MCR) concept for long-term effects, such as turning the entire system on, or starting a long sequence of actions.

Figure LC-6 below summarizes many of the design guidelines given above.

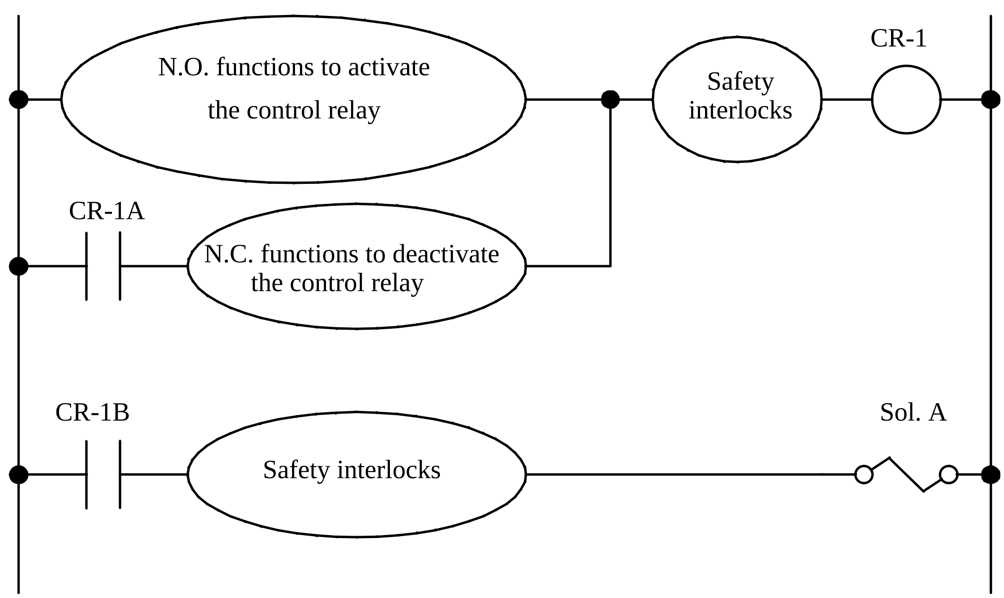


Figure LC-6. General logic design

Machine Safety

Jamming occurs when a cylinder is unable to complete a desired stroke. Pressure switches can be installed in the lines leading to the cylinder to indicate excessive pressure levels. Figure LC-7 shows a circuit with simple "jamming" protection. The cylinder normally retracts when it reaches the far limit switch, without a large increase in the system pressure. If a "jam" occurs, motion of the cylinder will stop and the pressure will rapidly increase. The pressure switch PS-9 will be activated which opens the normally closed contacts CR-9B. Solenoid SOL-A is prevented from being re-activated until the "jam" is cleared and the release button PB-9 is pressed.

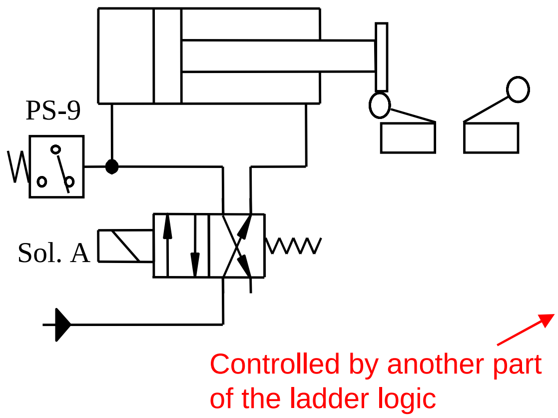


Figure LC-7: Cylinder "jamming" protection

Another consideration is important for double solenoid valves, which are common in hydraulic circuit designs. Most double solenoid valves cannot withstand simultaneous activation of both coils. One of the circuits shown in Figure LC-8 should be considered to prevent this occurrence. In both circuits, SOL-A and SOL-B are attached to the same solenoid valve. A single control relay (CR-1) is used in the left circuit to activate contacts (CR-1A and CR-1B) which cannot be closed simultaneously. The circuit on the right uses the same principle for each solenoid coil.

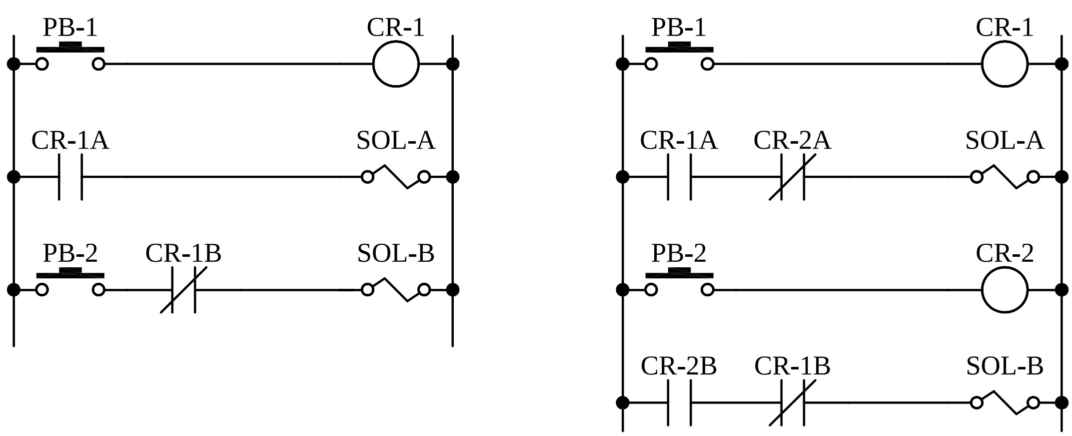


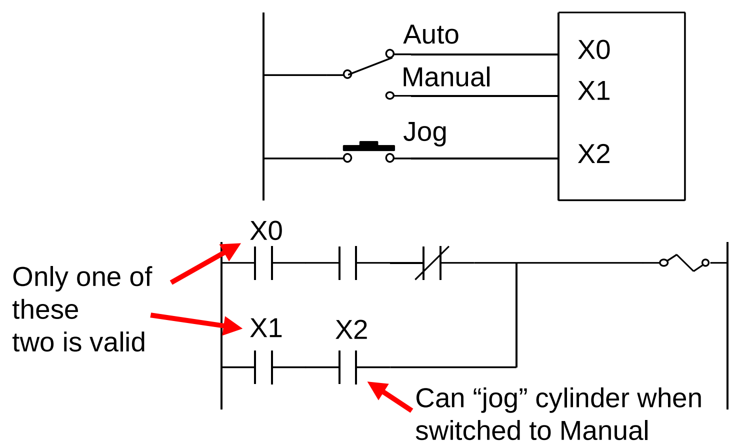
Figure LC-8: Prevention of simultaneous coil energizing

Operator Safety

The remaining safety topic for design consideration is operator safety. System designers must anticipate problems that might occur with their products and provide a safely operating system. At a minimum a designer should consider the following:

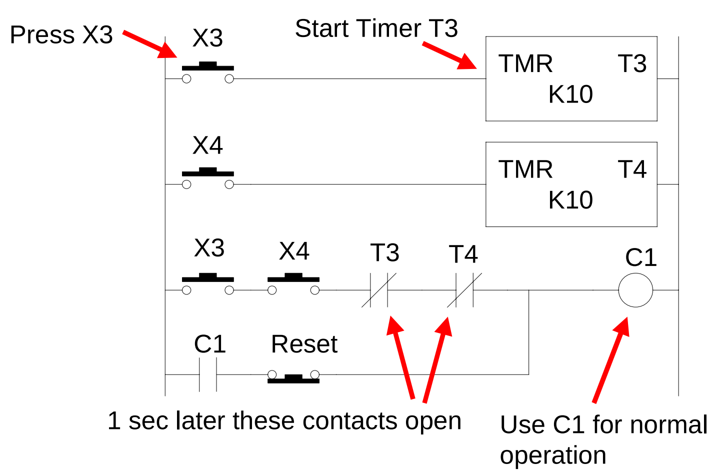
1) warning/operating signals,
2) emergency/"panic" stop, and
3) manual two-hand or "deadman" switch operation.

Warning and operating lights can easily be provided for a system by adding additional rungs to the ladder diagram. A large flashing (or strobe) light is often used to indicate that the system is powered and operating. Additional warning lights can be provided during critical portions of the operating cycle, such as rapid cylinder advances, clamping cycles, etc. Emergency (or "panic") buttons are usually large red palm buttons that have a detent mechanism which holds them closed once pressed. Emergency stops are usually wired to remove all power from valves as well as stopping a pump or activating an automatic relief. When using a PLC, it is generally preferable to place at least one emergency stop button outside the ladder logic, such that program malfunctions cannot prevent system shutdown. "Minor" emergencies can be handled with appropriate placement of push-buttons in the PLC ladder logic. If "emergencies" happen frequently, then the system design should provide for a stable, repeatable way to return the system to a start-up position. As a last resort, manual operation or jogging may be used to return the system to a start-up position.



A careful system designer will also consider operator actions that are not necessary or desirable for safe operations. Single manual push-buttons to start a system may be replaced with two push-buttons wired in series. These push-buttons are often physically spaced far apart such that both hands of an operator are required to press the buttons. A "deadman's" switch requires a continuous operator input maintain system output. A momentary contact switch <u>without</u> a control relay holding circuit will often suffice.

A common problem with manual two-hand systems is that one of the push-buttons is bypassed by an



operator (wedged closed with a screwdriver, taped down, or weighted). A "non-tie-down" circuit which prevents this action with a two-hand operation is shown on the right. This circuit requires that both input push-buttons (X3 and X4) be pressed within one second of each other. Pressing X3 will start the timer T3, which will open the normally closed contacts T3 after one second. Pressing X4 activates T4 in the same fashion. If both push-buttons are pressed within one second of each other, then control relay C1 will activate. Contacts associated with C1 are used to indicate a successful system start-up. If either of the input push-buttons is "tied-down", then the corresponding normally closed contact on the third rung will open and the control relay C1 will never be activated. In this example the reset push-button is provided to stop the system by breaking the holding circuit around C1.

References and Bibliography

1. Jones, C.T. and L.A. Bryan, *Programmable Controllers - Concepts and Applications,* International Programmable Controls/Astec, Atlanta, 1983

    A ten year old paperback book with an historical introduction and a wealth of information on PLC's. Although somewhat dated, much of the material is relevant to new automation systems and should be considered by users of industrial PLC's.

2. Pessen, D.W., *Industrial Automation - Circuit Design and Components,* John Wiley & Sons, New York, 1989

    A textbook which focuses on logic system programming, both ladder logic and discrete IC systems. Some background material on automation system components, including hydraulic, pneumatic, electrical, and electronic components along with industrial sensors.