5.2 Ladder Diagrams

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INTRODUCTION

Ladder diagrams are one of the traditional methods for describing logic control circuits, whether they are electrical, pneumatic, or hydraulic. Ladder diagrams sometimes are referred to as elementary diagrams or schematics. They are called so because of the vertical power rails and the horizontal rungs that are individual parallel circuits between the common power rails.

For the purpose of this discussion electrical symbols will be used. Boolean logic is used in these diagrams to represent switch and relay contacts. The basic ladder diagram symbols that are used in electrical ladder diagrams are described in this section. Also presented are examples that illustrate the connection between the process and the ladder diagram and that indicate the procedure for analyzing a ladder diagram to determine its control functions.

For the standard that describes the binary logic symbols and diagrams recommended by the Instrument Society of America, refer to Section 5.1. The ISA standard compiled for ladder diagrams and other process logic depictions is ISA-5.2-1976 (R1992), "Binary Logic Diagrams for Process Operations."

LADDER DIAGRAM SYMBOLS

Figure 5.2a describes a few of the common symbols that are used in ladder diagrams and will be discussed in this section. The top row of the symbols in this figure include two manually operated pushbuttons (P.B.s) and a selector switch.

In the symbol for the three-position, two-pole selector switch, "X" represents the closed and "O" represents the open state. The "XOO" notation adjacent to the first level (top) of the selector switch represents the states of the switch contact in each of the three selector switch positions. The multiple lines from the top of the switch show the number of positions the switch can take, and the line that is drawn heavily represents the position that corresponds to the state drawn in the figure.

The second row in Figure 5.2a shows a coil, which can be that of a starter, a relay, or a solenoid coil (relays are discussed in Section 5.9). This symbol often includes a letter to describe the type of coil used. Also shown in the second row of the figure are the symbols for a Normally Open (NO) and a Normally Closed (NC) relay contact.

The third row shows two forms of a pilot or indicator light and a symbol for a fuse. The fourth and fifth rows describe switch contacts of level, flow, temperature, and pressure switches that are activated by the process. The last row

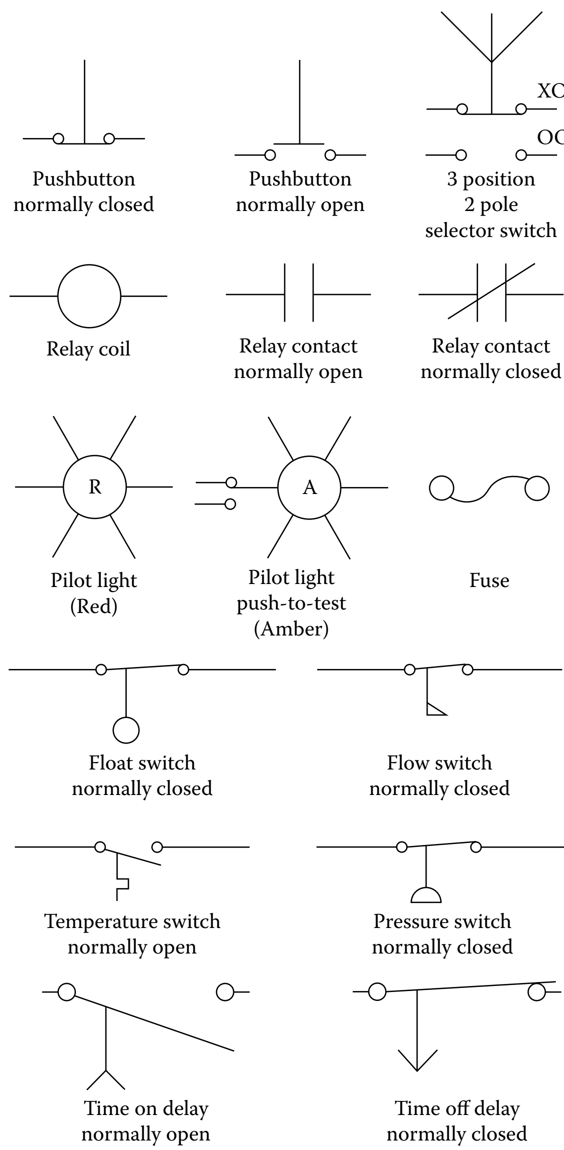

FIG. 5.2a
Sample of symbols used in ladder diagrams.

depicts two time delay relay contacts, one normally open, the other normally closed. If the time delay is used to delay the turning on of a device, it has an arrow pointing into the contact (left), and if it serves to delay the turning off of a device, it has an arrow pointing away from the contact (right).

Although there are a great number of other ladder diagram symbols, the set presented here is sufficient to enable the reader to understand the drawings presented in this section.

The wires in the ladder diagram should be labeled with unique alphanumeric identifiers. The rule of labeling is that an electrically common point of a circuit that will never be switched or disconnected will carry the same label. A variation of the above rule is to have a single wire number for each continuous circuit, but added to this number is a "subnumber" (-#) that changes at each termination point. For example, in the wire labels *D*1-47-1 and *D*1-47-2, *D*1 is the loop or device number, 47 is the wire number, and 1 and 2 are electrically the same wire but are connected at a terminal block.

DEVELOPING A LADDER DIAGRAM

Figure 5.2b illustrates the automatic control of a pressurized water tank and the ladder diagram of its automatic control circuit. The figure shows a water storage tank, a pressurized water tank, a pump, and some level switches and other devices required to control the system.

The ladder diagram of the system illustrates a control circuit, which has both an automatic and a manual mode of operation. The stop P.B. is usually located near L_1 before any

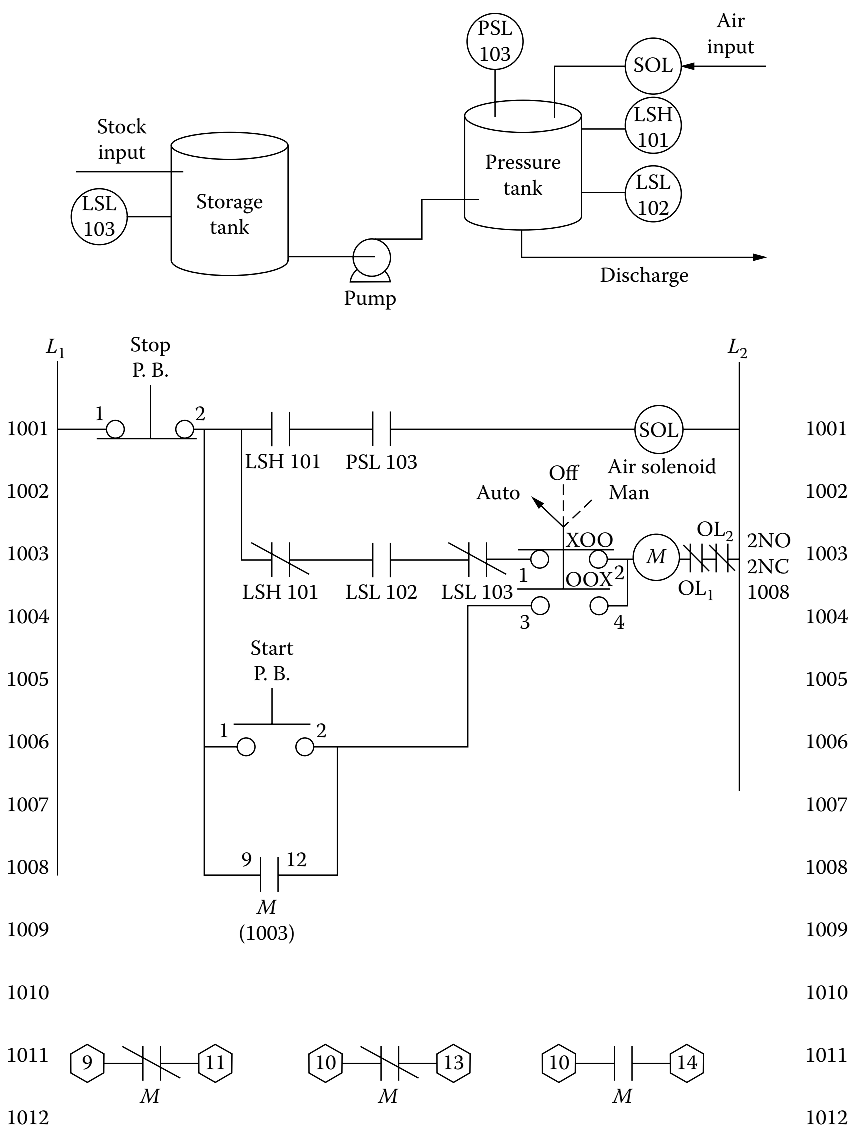

FIG. 5.2b
Automatic control of a pressurized water tank.

branches are added to the drawing. The manual control mode in this instance consists of only a start-and-stop pushbutton and the safety overload protection (OL_1 and OL_2) for the pump. These elements are shown in the ladder diagram and have been arranged so that the electrical connection from L_1 to L_2 will be made when the stop P.B. contact is closed, the start P.B. is pressed (contact closed), and the operating mode selector switch is in the "Auto" position.

L_1, on the left or power side of the ladder diagram, and L_2, on the right or neutral side, represent the power feed to the circuit. The normally open contacts (9 and 12), labeled "*M*," are activated (closed) when the pump relay is energized and keep the pump relay energized (engaged) even after the start P.B. has been released and therefore contacts 1 and 2 are open. This circuit is called a seal-in or latching circuit.

The common terminology for relay contacts is NO (Normally Open or Form *A*) and NC (Normally Closed or Form *B*). *A* Form *C* relay is one where the common power supply is connected to both an NO and an NC set of contacts. Refer to Section 5.9 for a more thorough description.

Automatic Mode of Operation

In the control system there is a high- and a low-level switch (LSH-101 and LSL-102) on the pressurized tank and a low-level switch (LSL-103) on the water storage tank. In addition there is a low-pressure switch (PSL-103) on the pressurized water tank. In preparing the ladder diagram for the corresponding control system, one should make sure that the water pump will be energized only when each of the control constraints have been satisfied and the electrical path from L_1 through the pump starter relay to L_2 has been completed.

The automatic portion of this water control circuit is presented in the top half of the ladder diagram in Figure 5.2b. In this control circuit, the electrical connection between L_1 and L_2 will only be made if the switch contacts shown in the figure are closed.

The high-level switch on the pressure tank (LSH-101) has two sets of contacts: a normally open set to control the operation of the air solenoid and a normally closed set to provide a limit condition for pump operation. The pump can only operate if, in addition to the level not being high (the NC LSH-101 contacts closed), the level is not low in the storage tank (the NC LSL-103 contact is closed) and the level is low in the pressurized tank (the NO LSL-102 contacts are closed). The pump starter coil will, therefore, be energized when the water level is low in the pressurized tank but will be deactivated (the pump will be stopped) when the water level is low in the storage tank.

This configuration will both protect the pump and maintain the pressure in the pressurized tank. To keep the water supply pump running, once the level in the pressurized tank drops to the low level switch (the NO contacts of LSL-102 are momentarily closed), an interlock with a set of pump relay contacts must be provided. The normally open contacts (9 and 12), labeled "M," are activated (closed) when the pump relay is energized, and they keep the pump relay energized (engaged) even after the level in the pressurized tank is no longer low (the NO contact of LSL-102 is open).

In Figure 5.2b the mode selection switch is placed near the starter relay and the normally closed contacts of LSL-103 and LSH-101 are placed in series with the normally open LSL-102 contacts. As it was the case in the manual mode of operation, a set of normally open starter relay contacts (9 and 12) ensure that the starter relay remains energized when the liquid level rises above the minimum set by LSL-102, but remains below the maximum set by LSH-101. Therefore, LSH 101 disengages (de-energizes) the relay when the level in the pressurized tank reaches its high set point.

When the NO contacts of this high water level switch (LSH-101) close, that will energize (open) the air solenoid, if the tank pressure is also below the setting of PSL-103 and therefore the NO contacts of that switch are closed.

SUMMARY

In summary, the steps required in developing a ladder diagram for a process control system include (1) to review the possible process conditions and the responses required, (2) to select the various switches and other control elements that can accomplish these required tasks, and (3) to arrange the system components in a sequential fashion between the voltage lines of the ladder diagram.

When the required response to a momentary condition is to latch in the state of operation, interlock contacts should be provided around start pushbuttons and other momentary contacts. Stop pushbuttons and other safety interlock contacts should be arranged so that they are electrically close to the source voltage line.

Each component of the drawing should be labeled by the same tag number that is used for the corresponding actual device in the process. Particular attention should be paid to identifying all of the contact sets of a specific relay coil. Finally, all automatic contacts of all switches and other actuating devices should be shown in a state (normally open or closed) that will exist when the device is in a de-energized (idle or inactive) state.

LADDER DIAGRAM ANALYSIS

The basic procedure for the analysis of a control circuit ladder diagram is to consider the diagram one component at a time and to decide what will happen if a pushbutton contact is closed or a switch contact is opened. If the ladder diagram is reviewed from this point of view, it will be noted that such contact activity usually closes or opens complete circuits and then a particular coil will be energized or de-energized, depending on the continuity of the circuit.

When the circuit is complete to any particular coil, that contactor, relay, or starter will be energized and the state of its contacts will be the opposite to its normal, de-energized position. If they are normally closed contacts, they will now be open, and if they are normally open, they will be closed.

When a time delay relay is used in the circuit, its contacts are opened or closed after some delay. If relays are used in the circuit, it is important to consider every contact that is operated by that relay whenever the coil is energized. Failure to consider all contact sets of a relay will result in a misconception of the function of the circuit. Finally, when analyzing a circuit, one should be certain that every component is considered in both its de-energized (normal) and energized position so that the whole operation of the complete circuit can be comprehended.

START-UP AND SHUTDOWN

In the design of a complex ladder logic it is very important to consider power-up and power-down sequences. In an electrical circuit the start-up and the shutdown are the times when strange and undesirable conditions can evolve. Typically, on power-up, if a circuit has a normally closed contact, this contact could cause a motor to start before it should, due to the dynamics of the circuit.

On the other hand, if there is a normally open circuit that prevents a device from running, this could prevent the device from ever starting unless manually started the first time. Also, when time delay relays are used, the circuit could be "locked out" until the time has elapsed and the relay has either energized or de-energized. This delay can be either intentional or unintentional.

Dynamic Breaking of a Motor

The ladder diagram of a motor's dynamic breaking circuit is shown in Figure 5.2c. This diagram can be reviewed by using the ladder diagram analysis procedures presented in this section. The example also provides insight into the concept of dynamic braking.

Dynamic braking can be applied to any equipment when a smooth, fast stop is required or when it is desired to prevent the manual rotation of the motor shaft when the power is disconnected. A dynamic braking system provides a stop without any tendency to reverse and it also produces less shock to motor drive components than does plug stop braking.

In a dynamic braking system, a DC voltage is applied to the rotating motor to provide a smooth but positive braking action and to bring the motor to a rapid stop. The DC signal is removed when the motor is almost stopped to prevent any motor winding damage caused by overheating as a result of excessive current flow in the low-resistance windings.

The diode rectifier element that produces the DC voltage is shown in the lower portion of the ladder diagram in Figure 5.2c. This part of the diagram also shows that the rectifier is isolated from motor terminals T_1 and T_3 by two sets of normally open brake coil contacts, B. There are also two sets

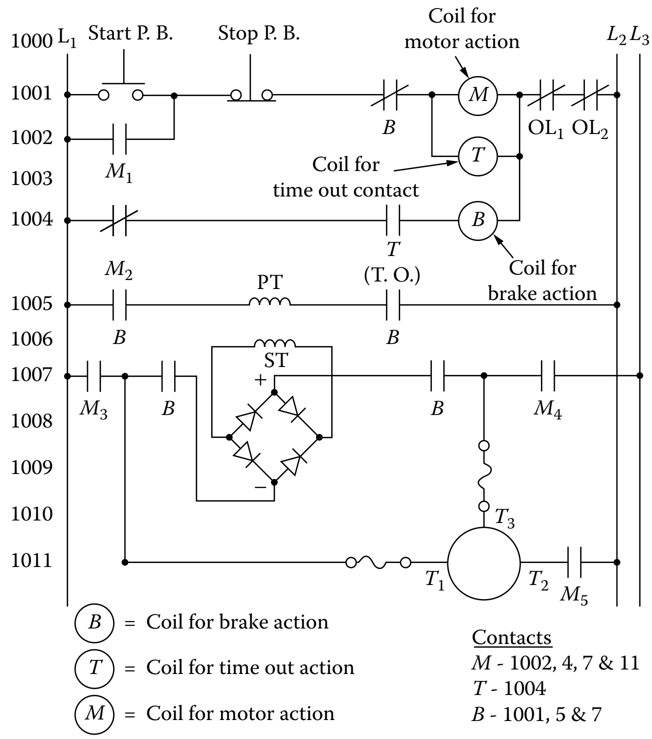

FIG. 5.2c
Ladder of a motor diagram for a dynamic braking circuit.

of normally open brake contacts that isolate the primary side of the transformer from power lines L_1 and L_2. The fifth contact controlled by the brake coil is a normally closed set that is in series with the motor relay coil and the start pushbutton.

If the motor start P.B. is depressed (provided that the safety overload contacts are closed) and the stop P.B. is not also depressed, then the motor relay coil is engaged and the five sets of motor relay contacts are activated. The first of these motor relay contacts, M_1, is illustrated in the top horizontal line of the ladder diagram. This normally open contact closes when the coil is energized to guarantee that the coil remains hot even after the start P.B. is released.

The second motor contact set, M_2, which is located on the drawing just below the first, is normally closed but is opened on motor coil activation to prevent the brake coil from receiving the L_1 signal. It should be noted that the normally open time-out contact, T, is closed because the time-out relay is also energized when the motor coil is active. The last three normally open motor contact sets are connected to the motor terminals and, when closed, provide a connection from the power lines to the three motor terminals.

The braking portion of the ladder diagram includes symbols for the brake relay, the time-out relay, the rectifier, the primary and secondary transformer elements, and the five brake contact sets. Figure 5.2c indicates that motor terminals T_1 and T_3 are connected to the DC terminals of the rectifier when the stop P.B. is pressed. When the stop P.B. is engaged, the motor relay is deactivated, the motor is isolated from the

AC lines, the time-out relay is dropped from the circuit, and the brake contacts are all activated.

The brake relay is energized because M_2 has returned to its idle state and the time-out contact, *T*, remains closed for the time-out period. Thus, the activated brake coil keeps the four normally open *B* contacts associated with the transformer and the rectifier closed until the time delay relay has timed out to force *T* to its normally open position. The actual time-out period is determined as a function of the time needed to bring the motor to a near stop.

FAIL-SAFE DESIGN

Another consideration in ladder design is the "what-if" aspect. What if a wire breaks or vibrates loose? Will an alarm condition occur that will go unnoticed because the alarm indicator never receives power, or will the alarm indicator become energized as a "default"? This part of the ladder diagram design is one of the most difficult to grasp. It can become a tail chasing the dog problem.

The general guiding rule is this question, "Which situation is worse, more catastrophic, or potentially life treating?" If an alarm is initiated when either the process is in alarm or when the alarm circuit has failed, that would be better than having a pumps seal water flow switch go into alarm but not realizing it until the motor bearings overheat and seize. This may require an additional relay, or a time delay relay, but the protection of safety and capital equipment will normally far outweigh any cost increase.

DOCUMENTATION

As in any design, good documentation is important. Several things can be done to allow for easier troubleshooting and for thorough documenting of design. Simple ladder diagrams as shown in the examples do not require any additional steps, but complicated diagrams do. The first thing that can be done is to run a number string down the side of the neutral and power side of the diagram with a number corresponding to each line space, whether a rung exists there or not. In other words, if rung spacing is every 0.75 in., the spacing (placement) of the numbers would also be 0.75 in.

To use these numbers, make note of the location of the use of each contact of a relay beside the coil location. This allows easier analysis of the logical use of the coil's activation. Second, it is good practice to note how many normally open and normally closed contacts are available on all coils. This enables the designer to know if there are any spare contacts available for modifications to the design.

Third, mark the terminal numbers for each contact or coil as well as any unused contacts. The unused contacts should be shown at the bottom of the rung column where the coil is used. This completely documents the circuit and the use of the components in it. Uniquely label each electrically common point in the diagram. These labels will be used on the wires in the physical circuit.

CONCLUSIONS

In summary, the proper procedure for ladder diagram analysis is to consider the circuit one component at a time and to decide what happens to the component when a contact is closed. In this process, one should determine the function of each component in its de-energized (normal) and energized positions and, finally, one should review the role of each component in relation to the other elements in the system.

It is important to perform a complete analysis of the diagram without jumping to conclusions halfway through the analysis. A hurried analysis can be disastrous, because the action of just one additional contact set can easily change the response or the basic nature of the circuit.

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