Unit 1

Basic Principles of Motor Control

UNIT OBJECTIVE

Upon completion of this unit, you will be able to identify and demonstrate the utility of different types of motor control and current protection devices. You will also be able to understand the operation of a lockout/tagout procedure.

DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

- Control description
- Safety procedures
- Three-phase distribution systems

DISCUSSION OF FUNDAMENTALS

Motor control is a broad term that can apply to anything from a simple toggle switch to a complex system with components such as **relays, contactors**, and **programmable logic controllers** (PLCs). The common function of all these controls is to command the operation of an electric motor.

A complete motor circuit is usually divided into control and power sections. The power circuit includes the motor and therefore, operates under higher voltage. On the other hand, the control part mostly contains switching devices and typically operates under lower voltage.

Control description

Control panel devices, such as push buttons, selectors, or toggle switches, command the operation of electric motors via their open or closed contacts, which transfer a control current.

Contactors and **control relays** are devices that use **electromagnetic induction** to open and close contacts. Contactors are often part of the motor starter, since they are power switching devices. Control relays are rather used as control switching devices, because they are designed to withstand lower electrical currents.

Motor starters are systems comprising switching and overload-protection components. They provide a safe, convenient, and economical means of starting and stopping motors.

Circuit breakers and fuses protect the motor from very high currents. Overload protection devices are safeguards against prolonged, relatively high current levels. The particular application of each motor and control installation must be considered when determining the protective devices required.

Safety procedures

Lockout/tagout procedures are measures taken to ensure the safety of workers during servicing and/or maintenance operations. When implemented correctly, all **energy sources** are isolated, which limits greatly the probability of accidents.

Three-phase distribution systems

Most domestic electrical systems are **single phase**, which means that there is only one live line per power outlet, along with a neutral wire and a ground wire.

Three-phase is another common electric power transmission method used for motors and many other industrial devices. Three-phase systems may have a neutral wire or no neutral wire.

Figure 1-1 shows the evolution of the three phases in time. With the help of this graph, it is possible to find the relationship between line–neutral and line–line voltages.

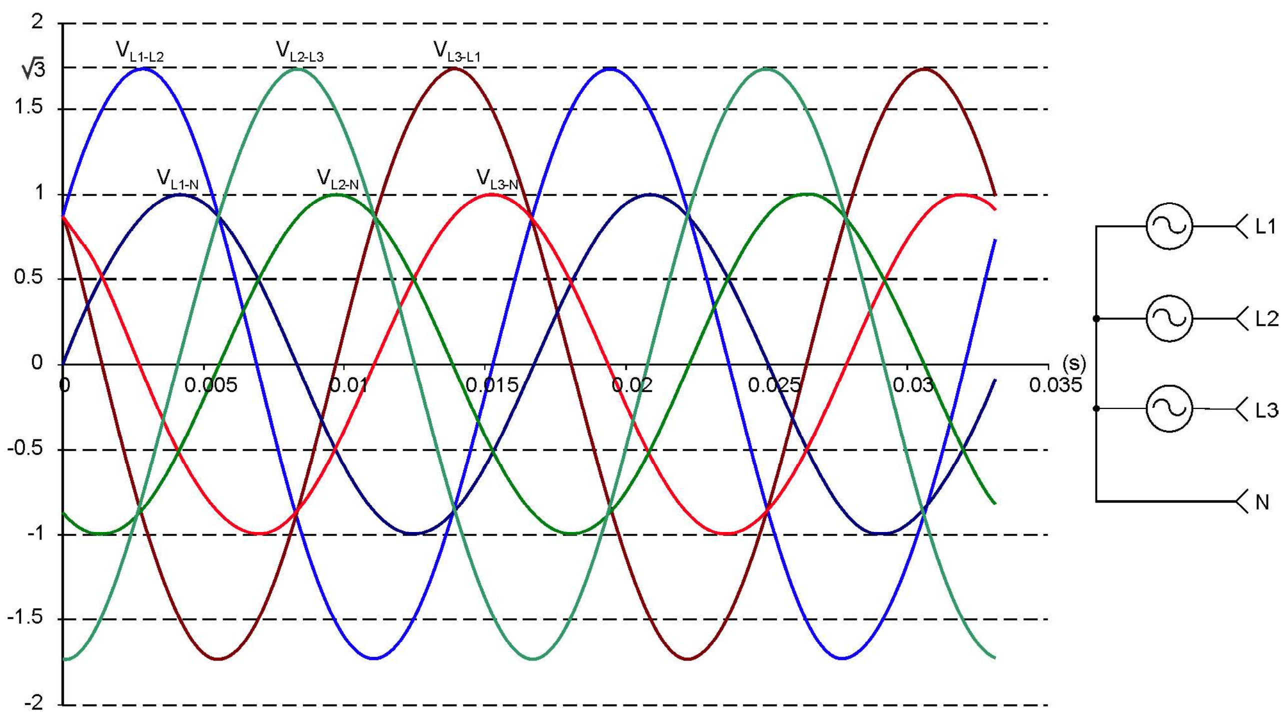


Figure 1-1. Three-phase distribution system.

Say, for instance, that we want to know the voltage between line 1 and line 2. We can subtract, for each time value, the L_{2-N} value from the L_{1-N} value to determine the desired line–line voltage (V_{L1-N} - V_{L2-N} = V_{L1-L2}). We observe that the peak amplitude of the obtained voltage V_{L1-L2} is $\sqrt{3}$ times the peak amplitude of the V_{L1-N}, V_{L2-N}, or V_{L3-N} voltages. The same principle applies to V_{L2-L3} and V_{L3-L1} voltages.

As an example, in North America, we find line–neutral voltages of 120 V and line–line voltages of 208 V ($\sqrt{3} \times 120$ V). This implies that a single phase load supports a higher voltage when it is located between two power lines than when it is located between a power line and a neutral line.

Note also, from Figure 1-1, that there is a 120-degree phase shift between each phase voltage. This is a very important feature, since electric motors using all three phases can easily produce a rotating magnetic field, hence greatly simplifying the machine design. Moreover, inverting two of the three phases has the effect of reversing the same rotating field, thus making the motor turn in the opposite direction.

Lockout/Tagout Procedure

EXERCISE OBJECTIVE

Become familiar with the Industrial Controls Training System.

Understand and perform proper lockout/tagout procedures during industrial servicing and/or maintenance operations.

DISCUSSION

Lockout/tagout procedures are measures taken to ensure that a machine or equipment, on which the personnel is working, is safe and cannot be powered unless every employee is ready.

Many pieces of machinery are potentially hazardous because of their purpose, the way they are built, or their location. Take, for example, a debarking machine (see Figure 1-2). It is equipped with several moving, sharp, and heavy parts. Servicing this type of equipment requires a number of safety precautions, because its accidental activation may very likely be disastrous.

Figure 1-2. Debarking machine (Image courtesy of USNR).

Prior to any operation on a machine or equipment, tasks that may expose workers to inadvertent release of hazardous energy must have been identified and proper training provided to the personnel. Sources of hazardous energy may be electrical, but also mechanical, hydraulic, pneumatic, chemical, thermal, gravitational, or others.

To make a machine or equipment safe:

- Notify all the affected employees that a procedure is going to be performed on a machine or equipment.
- De-energize the machine or equipment.
- Isolate and block all forms of hazardous energy, using locks and/or tags. In general, lockout devices should be preferred to tags. If more than one person is assigned to a task, all workers must use a personal and identifiable lock and/or tag at each **energy-isolating device**. A group lockout/tagout is also possible, provided that all workers are properly protected. The last hole of a hasp is usually reserved to accommodate an additional hasp.
- Verify that no one is near the machine or equipment and test if it is possible to start the equipment.

Special additional procedures may be required in cases where dangerous products like chemicals are involved.

When energizing a machine:

- Check that the machine or equipment is ready to operate, that the area is clear and secure, and that guards are positioned correctly.
- Notify all affected employees that the machine or equipment is about to be energized, and check that the workers are out of reach of the machine or equipment.
- Each worker must remove his own locks and tags. The machine or equipment must not be energized as long as a lock has not been removed by its owner.
- Start the equipment and make sure that it is working properly.

It should be remembered that each situation may require a particular procedure to ensure the safety of all workers. Therefore, please refer to the equipment manufacturer's documentation and to your local safety regulations for additional information.

A lockout/tagout procedure specific to the Industrial Controls Training System, Model 8036, is provided in Appendix D of this manual.

Procedure Outline

The Procedure is divided into the following sections:

- Equipment required
- Basic setup
- Line–neutral voltage
- Line–line voltage
- Lockout/Tagout procedure
- Fuse replacement

Procedure

In the first part of this exercise, you will connect the Lockout Module to the AC Power Supply module and verify that the output voltages are as stated in the theory of Unit 1.

You will carry out a lockout/tagout procedure before connecting a first electrical circuit. To help you with the setup, both a ***schematic diagram*** *and an interconnection diagram will be provided.*

In the circuit, a control transformer is connected through fuses between lines 1 and 2 of the Lockout Module module. This transformer provides control voltage that enables powering a pilot light without damage. An emergency button is located between the transformer and the pilot light, to allow you to turn off the light. Fuses inside the Fuse Holder module are deliberately blown, to make you practice fuse replacement.

Equipment required

Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required for this exercise.

WARNING

The AC Power Supply provides high voltages. Do not change any AC connection with the power on.

Basic setup

1. Perform the Basic Setup procedure described in Appendix D.

Line–neutral voltage

2. Connect the voltmeter between terminals L1 and N of the Lockout Module to measure the line–neutral voltage.

   Turn on the AC Power Supply by setting the individual power switch to the I position.

   Make sure that the main switch lever is set to the up position.

   Turn on the Lockout Module.

   Record the voltage displayed by the voltmeter.

$$E_{L1-N} = \_\_\_\_\_\_\_\_$$

Line–line voltage

3. Turn off the Lockout Module.

Connect the voltmeter between terminals L2 and L3 of the Lockout Module to measure the line–line voltage.

Turn on the Lockout Module.

Record the voltage displayed by the voltmeter.

$$E_{L2-L3} = \_\_\_\_\_\_$$

4. Do the voltages measured confirm the theory presented in the Discussion of Fundamentals? Explain why.

Lockout/Tagout procedure

5. Perform the Lockout/Tagout procedure described in Appendix D.

Fuse replacement

6. Connect the circuit shown in Figure 1-3.

When using the Fuse Holder, indicate the rating of the fuses on the module faceplate. Note the rating on three blank magnetic labels and install them above the fuse terminals. The rating of the fuses supplied with the training system is as follows (1.5 A for 220 and 240 V versions, and 3 A for 120 V version):

1.5 or 3 A 600 V ac	CLASS CC	TIME DELAY

To facilitate the understanding of the circuit shown in the picture, the ground connections are shown with green leads, and the other connections are shown with yellow leads. When setting up your circuit, use leads of appropriate length to connect the components, whatever the color. In the schematic diagram of the circuit shown in the picture (and for the other circuits to connect in this manual), however, the red color indicates a low voltage connection.

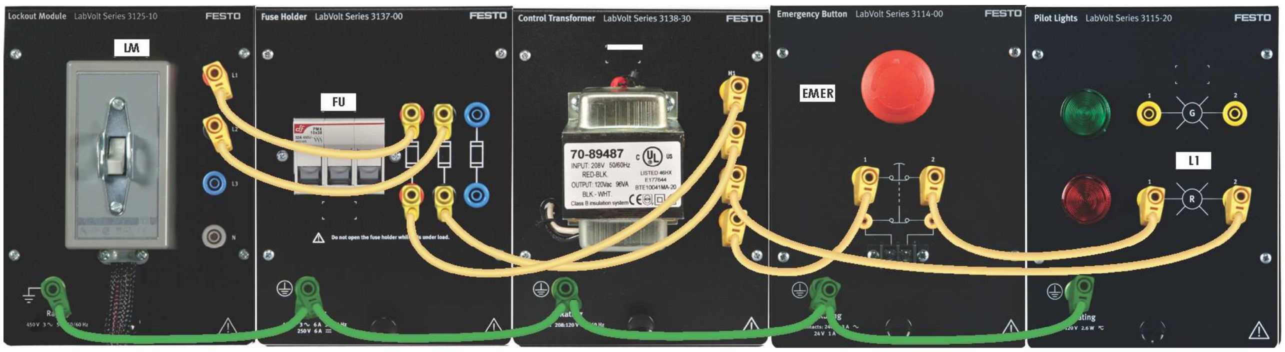
7. Make sure that the push button of the Emergency Button module is released.

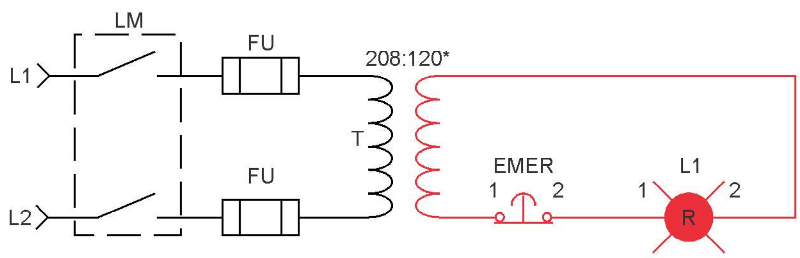
   In case of doubt, press the Emergency Button and turn it in the counterclockwise direction to reset the button to the release position.

   Perform the Energizing procedure described in Appendix D.

   After the Lockout Module is turned on, does the L1 pilot light turn on?

   ❑ Yes ❑ No





*208:120 FOR 120 V - 60 Hz NETWORK
380:110 FOR 220 V - 50 Hz NETWORK
415:110 FOR 240 V - 50 Hz NETWORK
380:120 FOR 220 V - 60 Hz NETWORK

LEGEND

EMER = EMERGENCY PUSH BUTTON (MAINTAINED CONTACT)
FU = FUSE
L1 = PILOT LIGHT (RED)
LM = LOCKOUT MODULE
T = CONTROL VOLTAGE TRANSFORMER

Figure 1-3. Basic circuit with the Lockout Module.

8. Turn off the Lockout Module.

   Remove the fuses from the Fuse Holder module and check them with an ohmmeter. Are the fuses blown?

   ❑ Yes ❑ No

9. Install new fuses (not blown) in the Fuse Holder module.

   Turn on the Lockout Module. Does the L1 pilot light turn on?

   ❑ Yes ❑ No

10. Describe what happens when you press the Emergency Button, and then reset it.

   ____

   ____

   ____

11. Turn the individual power switch of the AC Power Supply off, disconnect the circuit, remove the magnetic labels, and return the equipment to the storage location.

CONCLUSION

Lockout/Tagout procedures are meant to provide maximum security to every worker performing servicing or maintenance on a piece of equipment. These procedures imply isolating all sources of energy with personal locks and tags.

REVIEW QUESTIONS

1. What is the utility of a lockout/tagout procedure?

   a. Identify a machine or piece of equipment.

   b. Secure a machine or piece of equipment for servicing or maintenance.

   c. Reduce production losses.

   d. Complicate worker's life.

2. What do you have to do if there is only one hole left in the hasp of the equipment you are going to service, and more workers are going to work on that same equipment?

   a. Install another hasp in this last hole, in which you install your padlock and tag.

   b. Install the supervisor's padlock.

   c. Install only a tag.

   d. No more padlocks are necessary because there are enough padlocks already.

3. What source(s) of energy can be hazardous during lockout/tagout procedures?

   a. Mechanical

   b. Electrical

   c. Gravitational

   d. Hydraulic

   e. All of the answers above are correct.

4. Where do locks and tags have to be put?

   a. On the equipment.

   b. On the machine.

   c. On each energy-isolating device.

   d. On the main power supply.

5. Who is required to install at least one padlock during a lockout procedure?

   a. All the affected employees.

   b. The supervisor only.

   c. All the employees working on the machine or equipment.

   d. Only the trainees.

Exercise 1-2

Control Panel Devices

EXERCISE OBJECTIVE Verify the operation of selected motor control devices.

DISCUSSION OUTLINE The Discussion of this exercise covers the following points:

- Push buttons
- Selector and toggle switches
- Pilot lights

DISCUSSION A motor controller is a device or group of devices that commands the operation of an electric motor, using **normally open** (NO) and **normally closed** (NC) contacts. NO contacts are closed only when actuated. NC contacts work in the opposite way, they are open when actuated.

A motor controller has one or more of the following capabilities. It may cause the motor to:

- start or stop;
- rotate forward or reverse;
- have its speed or torque limited or regulated;
- be protected against overloads and faults.

There are many factors to consider when selecting and installing motor control devices for use with particular machines or systems. For example, to start or stop a motor, here are some considerations that may influence the choice of a motor controller:

- characteristics of the motor;
- number of starts and stops in a cycle;
- light or heavy loads when starting or stopping;
- fast or slow stopping;
- need for accurate stopping;
- manual or automatic starting and stopping;
- installation and operating costs.

Once the conditions are met, the motor may be controlled safely and efficiently.

Push buttons

Push buttons are switches that provide control of a motor by pressing a push button. Push buttons usually have a set of NO and NC contacts which change state momentarily when the push button is pressed.

Figure 1-4 shows the Push Buttons module, Model 3110-2. The green push button is usually used along with its NO contact as a start push button. The red push button is usually used along with its NC contact as a stop push button. For security reasons, stop push buttons are more easily accessible than start push buttons.

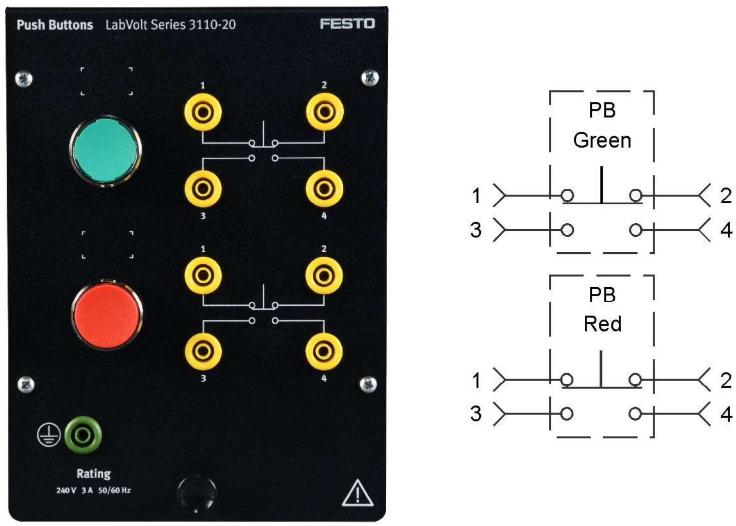


Figure 1-4. Push Buttons, Model 3110.

Selector and toggle switches

The Selector Switches module, Model 3111-2, allows you to alternate between two control circuit branches through the selector (at the top) or the toggle (at the bottom) switches. The two switches work independently. Selecting a position activates or deactivates the maintained contacts. Figure 1-5 shows the Selector Switches module and its diagrams.

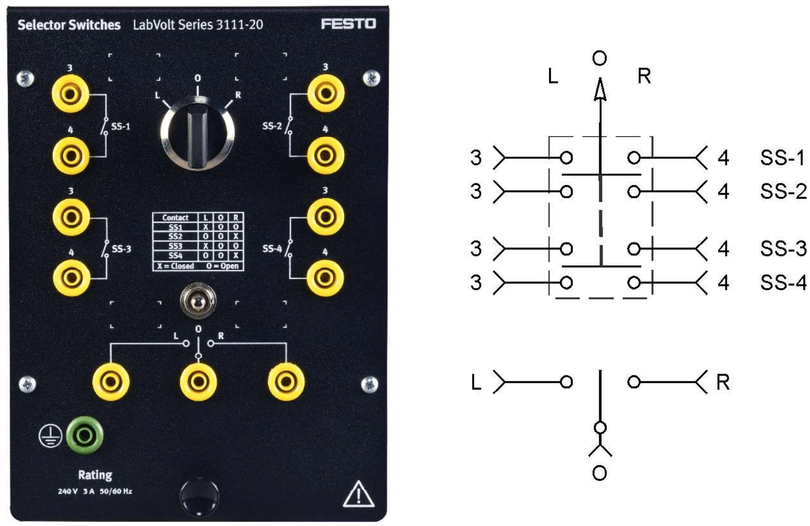


Figure 1-5. Selector Switches, Model 3111.

Pilot lights

Pilot lights, which are usually red or green, are used to indicate if the line is energized, or if the motor is running. Figure 1-6 shows the Pilot Lights module, Model 3115-2.

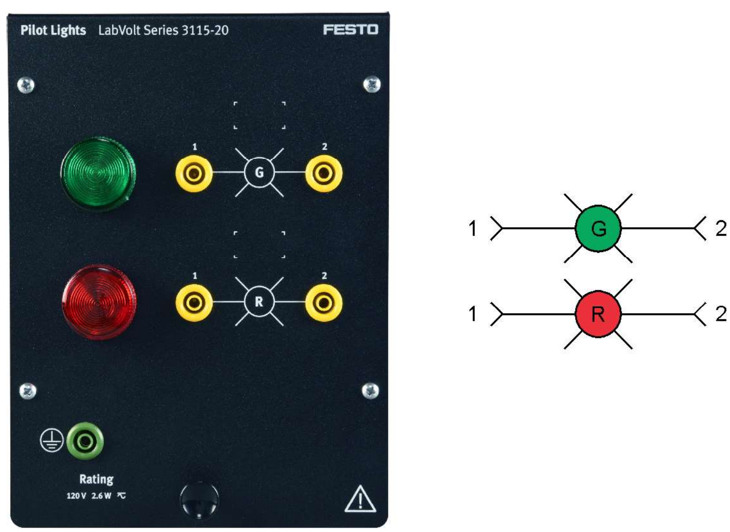


Figure 1-6. Pilot Lights, Model 3115.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Basic setup
- Momentary contacts
- Maintained contacts

PROCEDURE

In the first part of this exercise, you will use one NO and one NC push button contact to power two pilot lights. This procedure will demonstrate that push button contacts are momentary. Once again, it is necessary to use the Control Transformer in order to obtain a voltage compatible with the Pilot Lights module.

In the second part of the exercise, you will use a similar circuit, in which a toggle switch is employed instead of the push buttons. You will observe that the toggle switch differs from the push buttons in that it has a maintained contact.

In the third part of the exercise, you will verify, with the help of an ohmmeter, that the behavior of the selector switch corresponds to the indications provided on its module faceplate.

⚠ WARNING

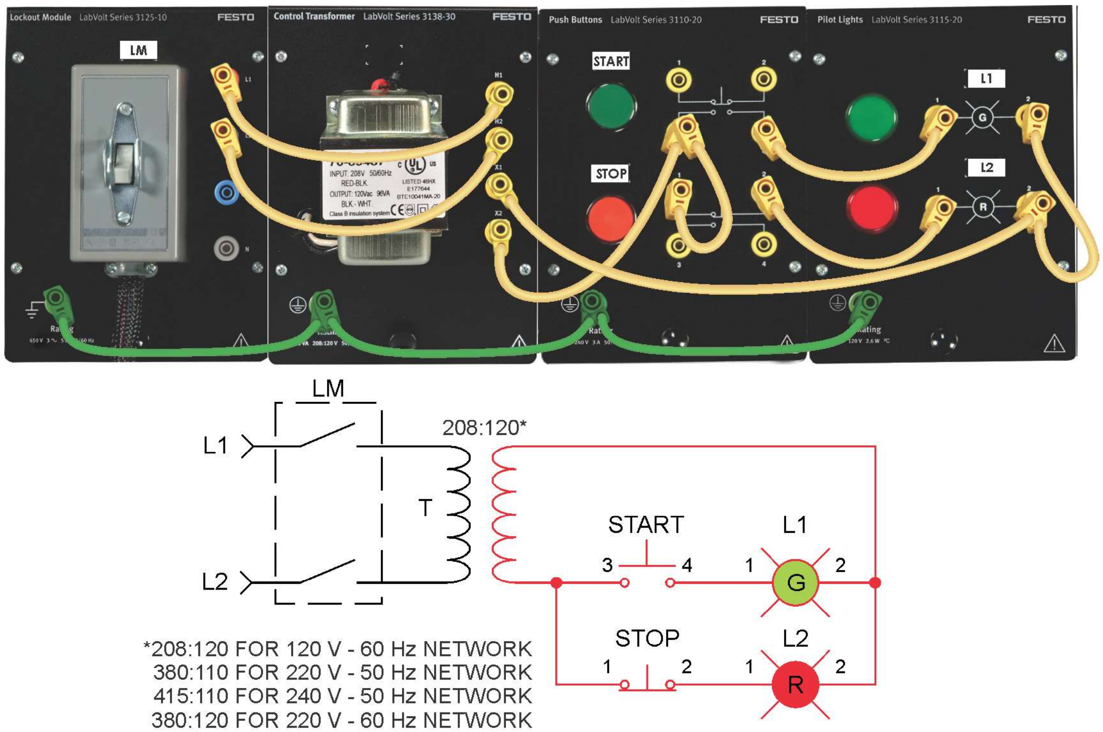
The AC Power Supply provides high voltages. Do not change any AC connection with the power on.

Basic setup

1. Perform the Basic Setup and Lockout/Tagout procedures.

Momentary contacts

2. Connect the circuit shown in Figure 1-7.



LEGEND

L1	=	PILOT LIGHT (GREEN)
L2	=	PILOT LIGHT (RED)
LM	=	LOCKOUT MODULE
START	=	START PUSH BUTTON (MOMENTARY CONTACT)
STOP	=	STOP PUSH BUTTON (MOMENTARY CONTACT)
T	=	CONTROL VOLTAGE TRANSFORMER

Figure 1-7. Basic push button circuit.

3. Perform the Energizing procedure.

4. After the Lockout Module is turned on, which pilot light(s) illuminate(s) when:

   - no push button is pressed?

     ❑ L1 pilot light ❑ L2 pilot light ❑ Both ❑ None

   - only the START push button is pressed?

     ❑ L1 pilot light ❑ L2 pilot light ❑ Both ❑ None

   - only the STOP push button is pressed?

     ❑ L1 pilot light ❑ L2 pilot light ❑ Both ❑ None

   - both push buttons are pressed?

     ❑ L1 pilot light ❑ L2 pilot light ❑ Both ❑ None

5. Following your last observations, what type of contacts are connected to:

- push button terminals 1-2?

  ❑ Normally open ❑ Normally closed

- push button terminals 3-4?

  ❑ Normally open ❑ Normally closed

6. Does the state of a pilot light associated with a push button change when the button is released?

❑ Yes ❑ No

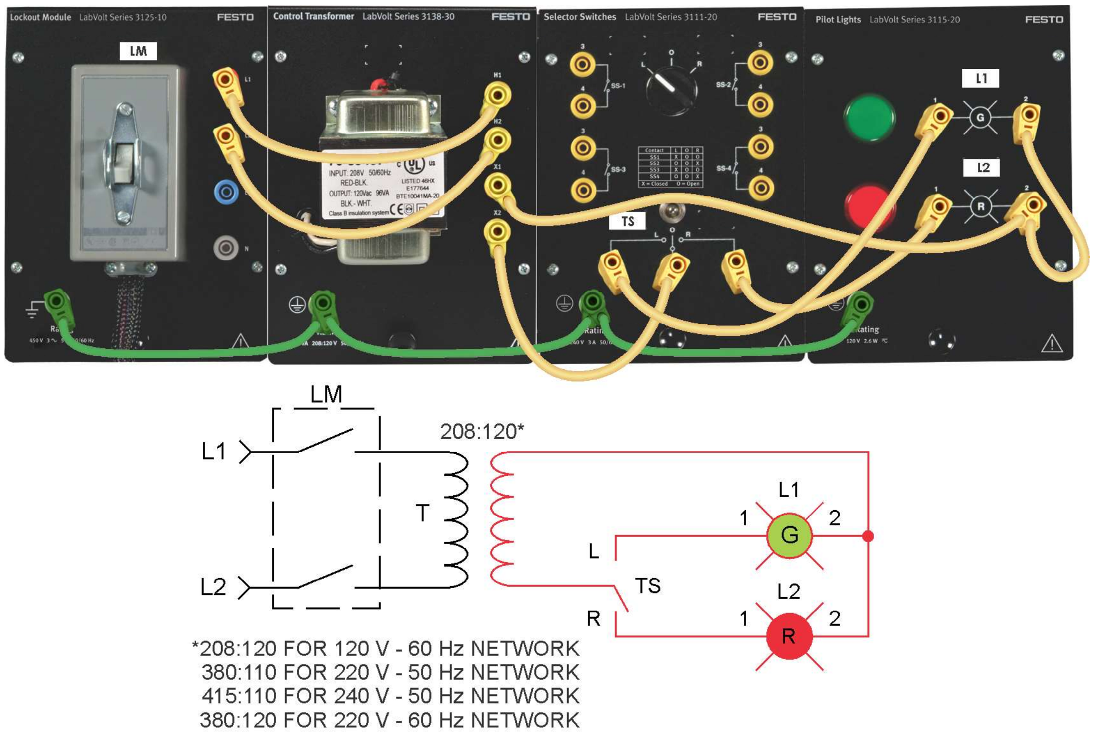
7. How can we characterize the Push Buttons module contacts?

❑ Maintained ❑ Momentary

Maintained contacts

8. Perform the Lockout/Tagout procedure.

Connect the circuit shown in Figure 1-8.



LEGEND

L1	=	PILOT LIGHT (GREEN)
L2	=	PILOT LIGHT (RED)
LM	=	LOCKOUT MODULE
TS	=	TOGGLE SWITCH (MAINTAINED CONTACT)
T	=	CONTROL VOLTAGE TRANSFORMER

Figure 1-8. Basic toggle switch circuit.

9. Set the TS toggle switch of the Selector Switches module to the O position.

10. Perform the Energizing procedure.

After the Lockout Module is turned on, does a pilot light illuminate? Explain why.

____

____

11. Set the TS toggle switch to the L position.

Which light illuminates?

❑ L1 pilot light ❑ L2 pilot light ❑ Both ❑ None

12. Set the TS toggle switch to the R position.

Which light illuminates?

❑ L1 pilot light ❑ L2 pilot light ❑ Both ❑ None

13. Does the toggle switch contact return to its original state after you release it?

❑ Yes ❑ No

14. How can we characterize the toggle switch contacts?

❑ Maintained ❑ Momentary

15. Turn off the Lockout Module.

16. Using an ohmmeter, determine which contacts of the Selector Switches module are closed when the selector is set to a specific position. Fill out Table 1-1 by putting an "X" mark when a contact is closed.

You will learn later in this manual that this type of table, showing the different contact states of a device, is called a target table.

Table 1-1. Target table of the Selector Switches module.

Contact	Selector position		
	L	O	R
SS-1			
SS-2			
SS-3			
SS-4			

17. Does your table correspond to the one located on the module faceplate?

❑ Yes ❑ No

18. Turn the individual power switch of the AC Power Supply off, disconnect the circuit, remove the magnetic labels, and return the equipment to the storage location.

CONCLUSION

Motor controllers command the operation of electric motors through normally open (NO) and normally closed (NC) contacts.

Push button, and toggle and selector switches are common manual controllers. The state of their contacts change as a push button is pressed, or the position of a toggle or knob is modified.

Pilot lights are used to show the condition of a circuit.

REVIEW QUESTIONS

1. What is meant by normally open contacts?

   a. Contacts that allow current flow when they are perturbed.

   b. Contacts that prevent current flow when they are perturbed.

   c. Contacts that allow current flow when they are at their normal position.

   d. Contacts that are always open.

2. When is the normally open contact of a push button actuated?

   a. When the push button is released.

   b. When the push button is pressed.

   c. When the coil is energized.

   d. When the coil is de-energized.

3. Why is the red (stop) push button standing out compared to the green (start) one on the Push Buttons module?

   a. For security reasons.

   b. A stop push button has to be easily accessible.

   c. A start push button must not be actuated accidentally.

   d. All of the answers above are correct.

4. Which of the following conditions may affect the choice of the motor controller to be used?

   a. Characteristics of the load.

   b. Time required to stop.

   c. Accuracy of control.

   d. All of the answers above are correct.

5. What color is generally used for a stop push button?

   a. Blue

   b. Yellow

   c. Red

   d. Green

Manual Starters

EXERCISE OBJECTIVE

Examine and describe the operation of manual motor starters.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Direct-on-line (DOL) starters
- Reversing starters

DISCUSSION

Motor starters are made of power switches and overload protection devices. They can be operated manually or remotely, through a magnetic contactor commanded by a control circuit. Full or reduced voltage can be applied to the motor, depending on the application.

Three-pole starters are used with motors operating on three-phase systems. The number of poles in these starters refers to the number of power contacts and does not include control contacts for control circuit wiring.

Two basic configurations of manual motor starters will be presented in this exercise, namely the **direct-on-line** (DOL), also called **across-the-line** or **full-voltage starter**, and the reversing starter. Magnetic motor starters will be seen in Unit 3, and reduced voltage motor starting methods will be seen in Unit 5 of this manual.

Direct-on-line (DOL) starters

DOL starters are the simplest way of starting a motor. A manual contactor is combined with an overload protection device. Figure 1-9 shows the Manual Starter, Model 3126, which can be used as a motor starter in both single-phase and three-phase operation. This particular module has a manual contactor, an adjustable overload protection, plus a circuit breaker. This is a DOL-type starter because full voltage is applied directly to the motor.

Reversing starters

Reversing starters are designed to make motors change direction by interchanging two of the motor power lines. **Cam switches** can be used for that purpose, with the addition of overload protection.

A cam (or **drum**) switch allows you to change between 2 or 3 operating modes, using a control knob to switch power lines directly. Figure 1-10 shows the Cam Switch module, Model 3140.

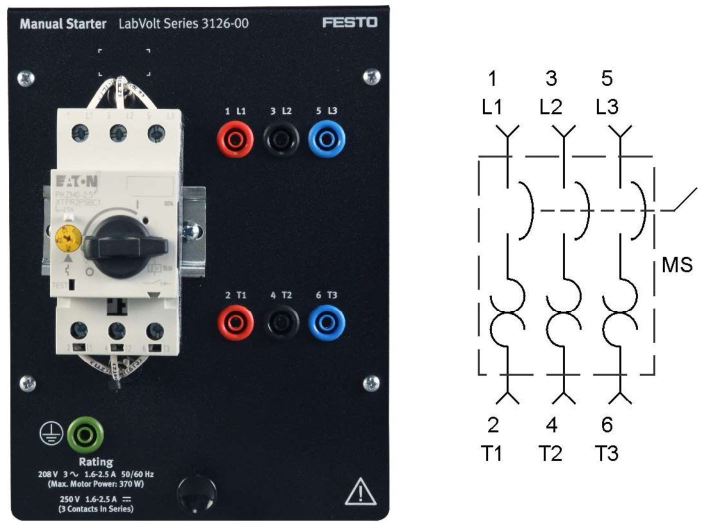
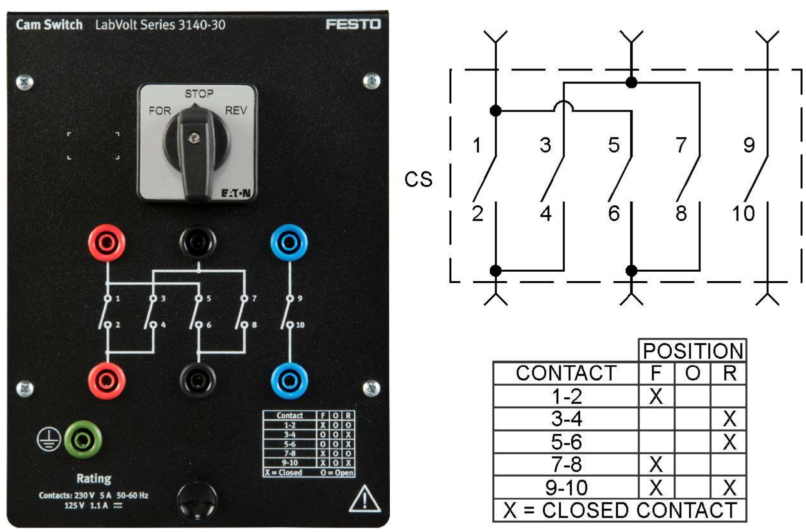


Figure 1-9. Manual Starter, Model 3126.



CONTACT	POSITION F	O	R
1-2	X		
3-4			X
5-6			X
7-8	X		
9-10	X		X
X = CLOSED CONTACT			

Figure 1-10. Cam Switch, Model 3140.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Basic setup
- Direct-on-line (DOL) starter
- Cam switch reversing circuit

PROCEDURE

In the first part of this exercise, you will examine the Manual Starter and determine that it has both the power contacts and the overload protection necessary to be called a motor starter. You will then test the Manual Starter with push buttons and pilot lights, and see that power lines are not reversed by the device, making it a DOL starter.

In the second part of the exercise, you will inspect the Cam Switch to find out that it does not include an ***overload relay****, and hence, cannot be considered a motor starter. After that, you will connect the Cam Switch to push buttons and pilot lights, and see that two power lines are inverted when switching between the forward and the reverse modes. You will observe that the Cam Switch can thus be part of a reversing starter.*

Basic setup

1. Perform the Basic Setup and Lockout/Tagout procedures.

Direct-on-line (DOL) starter

2. Examine the Manual Starter module. What is the range of the Manual Starter overload (indicated on the module faceplate)?

   Overload current range: __________

3. What is the purpose of the black knob on the Manual Starter?

   ____

   ____

4. What is the purpose of the yellow potentiometer on the Manual Starter?

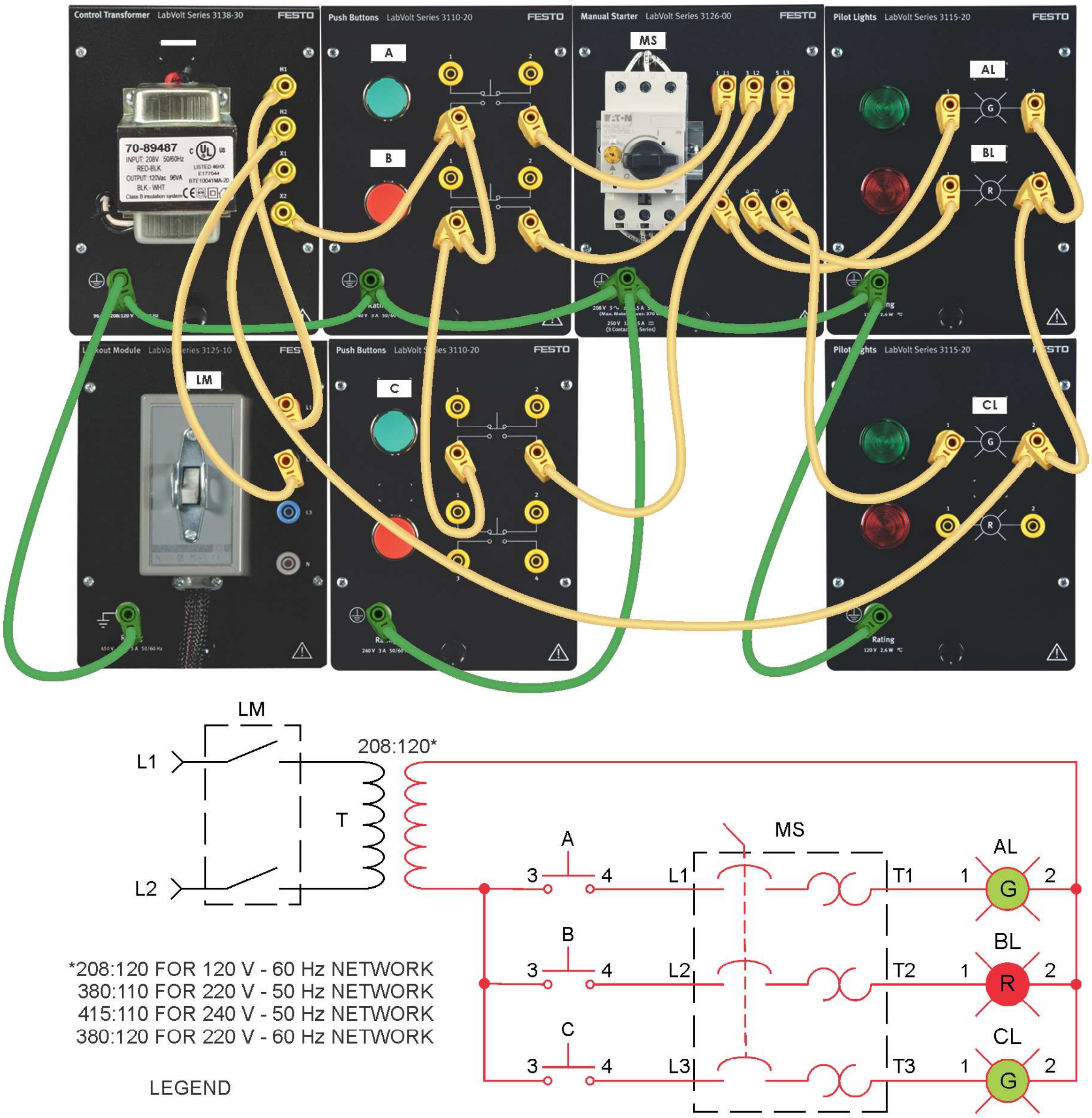
   ____

   ____

5. Is it appropriate to call this device a motor starter? Explain why.

   ____

6. Connect the circuit shown in Figure 1-11.



LEGEND

A	=	PUSH BUTTON A (MOMENTARY CONTACT)
AL	=	PILOT LIGHT A (GREEN)
B	=	PUSH BUTTON B (MOMENTARY CONTACT)
BL	=	PILOT LIGHT B (RED)
C	=	PUSH BUTTON C (MOMENTARY CONTACT)
CL	=	PILOT LIGHT C (GREEN)
LM	=	LOCKOUT MODULE
MS	=	MANUAL STARTER (CIRCUIT BREAKER WITH OVERLOAD)
T	=	CONTROL VOLTAGE TRANSFORMER

Figure 1-11. Basic manual starter circuit.

7. Set the knob of the Manual Starter to the O position.

Perform the Energizing procedure.

8. Set the knob of the Manual Starter to the I position.

9. Find out which lights illuminate when you press the push buttons. Fill out Table 1-2 for all three push buttons.

Table 1-2. Target table of a DOL starter.

Push button pressed	Pilot light illuminated		
	AL	BL	CL
A			
B			
C			

10. What type of starter is it?

❑ DOL starter ❑ Reversing starter

11. Perform the Lockout/Tagout procedure.

Cam switch reversing circuit

12. Examine the Cam Switch module. Does this module permit on and off switching?

❑ Yes ❑ No

13. What are the operating modes of this module?

____

14. Does the Cam Switch incorporate an overload relay?

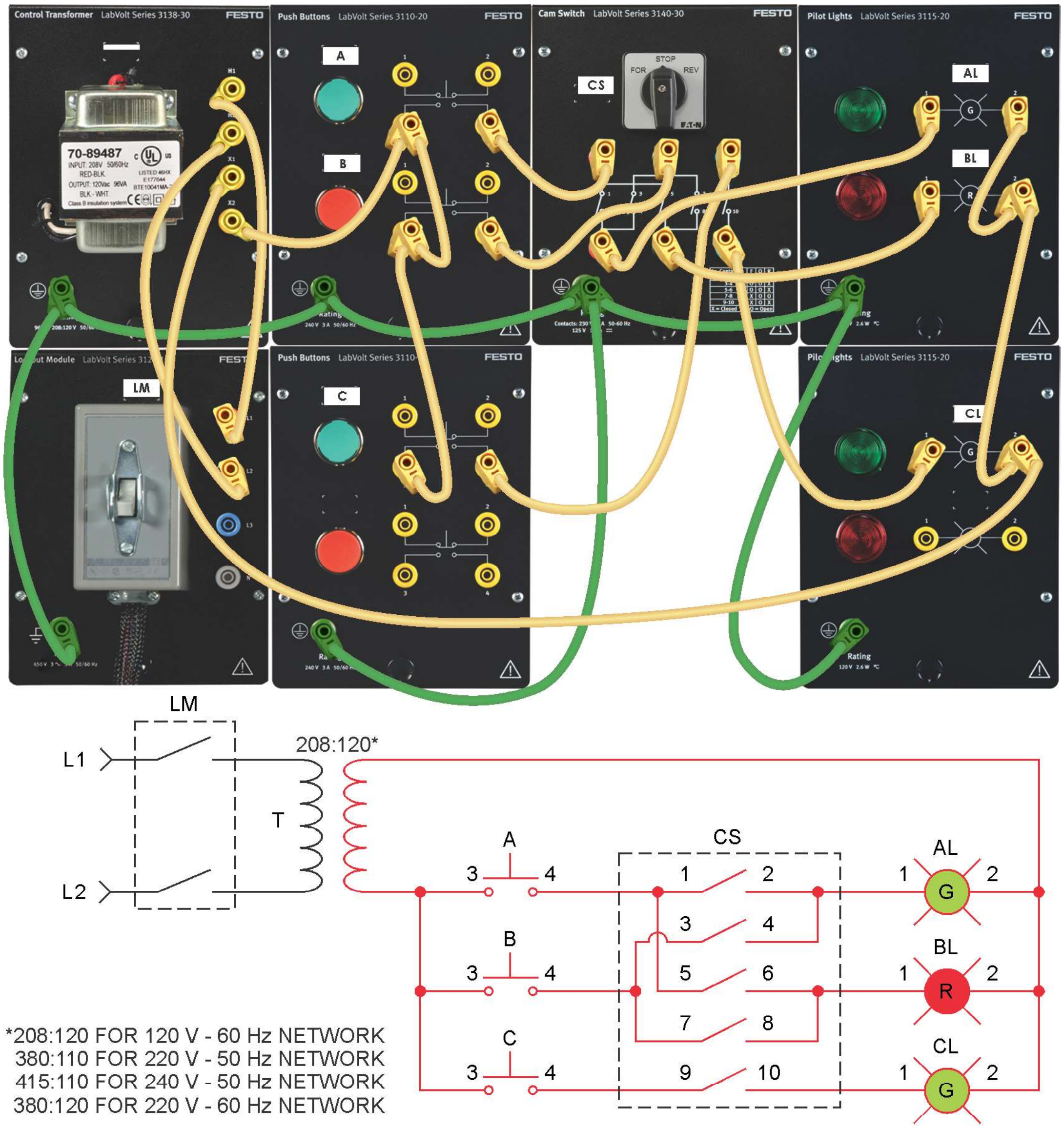
❑ Yes ❑ No

15. Is it appropriate to call this device a motor starter? Explain why.

____

____

16. Connect the circuit shown in Figure 1-12.



LEGEND

A	=	PUSH BUTTON A (MOMENTARY CONTACT)
AL	=	PILOT LIGHT A (GREEN)
B	=	PUSH BUTTON B (MOMENTARY CONTACT)
BL	=	PILOT LIGHT B (RED)
C	=	PUSH BUTTON C (MOMENTARY CONTACT)
CL	=	PILOT LIGHT C (GREEN)
CS	=	REVERSING 3-POLE CAM SWITCH
LM	=	LOCKOUT MODULE
T	=	CONTROL VOLTAGE TRANSFORMER

Figure 1-12. Cam Switch reversing circuit.

17. Perform the Energizing procedure.

18. Find out which pilot lights illuminate when you press the push buttons. Fill out Table 1-3 for all three push buttons in FORW (FDW), STOP, and REV modes.

Table 1-3. Target table of the Cam Switch.

Push button actuated	Cam switch position	Pilot light illuminated		
		AL	BL	CL
A	FORW (FDW)			
	STOP			
	REV			
B	FORW (FDW)			
	STOP			
	REV			
C	FORW (FDW)			
	STOP			
	REV			

19. Compared to the FORW (FDW) mode, which lines have been switched in the REV mode?

❑ 1 and 2 ❑ 1 and 3 ❑ 2 and 3 ❑ None

20. What type of starter can be constructed with the Cam Switch and an appropriate overload relay?

❑ DOL starter ❑ Reversing starter

21. Turn the individual power switch of the AC Power Supply off, disconnect the circuit, remove the magnetic labels, and return the equipment to the storage location.

CONCLUSION

Contactors and overload protection devices are the essential elements of motor starters.

DOL starters are the simplest method of starting a motor. They provide on/off control for small motors. The Manual Starter module is an example of a DOL starter.

Reversing starters reverse the direction of the motor by inverting two motor power lines. The Cam Switch module, with the addition of an overload relay, can be used for that purpose.

Review Questions

1. What are the two basic elements of a motor starter?

   a. Contactors and overload protection devices.

   b. Contactors and resistors.

   c. Resistors and fuses.

   d. Overload protection devices and timing relay.

2. What does the term direct-on-line refer to when talking about motor starters?

   a. The motor is controlled through a computer network.

   b. Reduced voltage is applied to the motor.

   c. A delta connection is used.

   d. Full voltage is applied directly to the motor.

3. What does the term three-pole refer to when talking about motor starters?

   a. Number of auxiliary contacts.

   b. Number of windings.

   c. Number of control contacts.

   d. Number of power contacts.

4. How does a reversing starter reverse the direction of rotation of a three-phase motor?

   a. By reversing the polarity of the phases.

   b. By interchanging any two phases to the motor.

   c. By opening one of the 3 contacts.

   d. By adding resistors in parallel.

5. What controller can be used to directly invert motor power lines?

   a. Lockout module

   b. Push button

   c. Cam switch

   d. Overload relay

Contactors and Control Relays

EXERCISE OBJECTIVE Identify the characteristics of control relays and contactors.

DISCUSSION OUTLINE The Discussion of this exercise covers the following points:

- Contactors
- Control relays

DISCUSSION

Contactors and control relays are switching devices providing electrical isolation between the control signals and the commanded electrical circuits. Different combinations of normally open and normally closed contacts are used to open and close circuits.

Solenoids, such as the one shown in Figure 1-13, are extensively used to operate contactors and control relays. Placing a coil of wire around a soft iron core sets up a magnetic flux. When energized, a **magnetic field** is developed around the coil. A north and a south pole are created and the iron core becomes a temporary magnet. As a result, a moveable plunger is attracted to the coil, and contacts attached to the plunger change state.

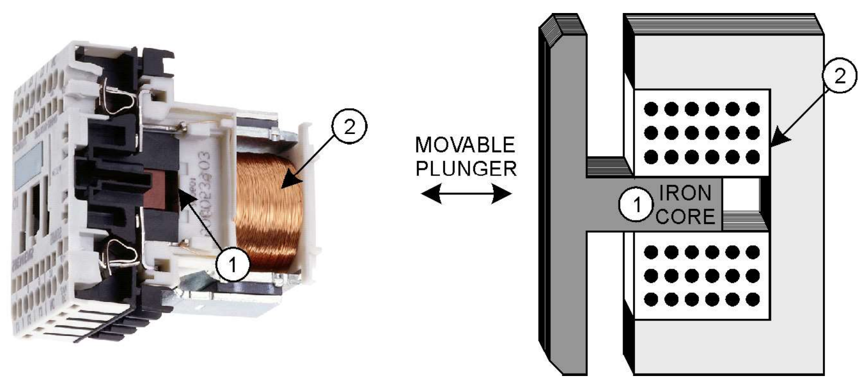


Figure 1-13. Basic magnetic core and coil.

When the coil is de-energized, the force of gravity or spring tension releases the plunger from the magnet body, causing the electrical contacts to return to their original state.

The same principle applies to single- and three-pole circuits. Figure 1-14 shows the motion of a single-pole magnetic contactor.

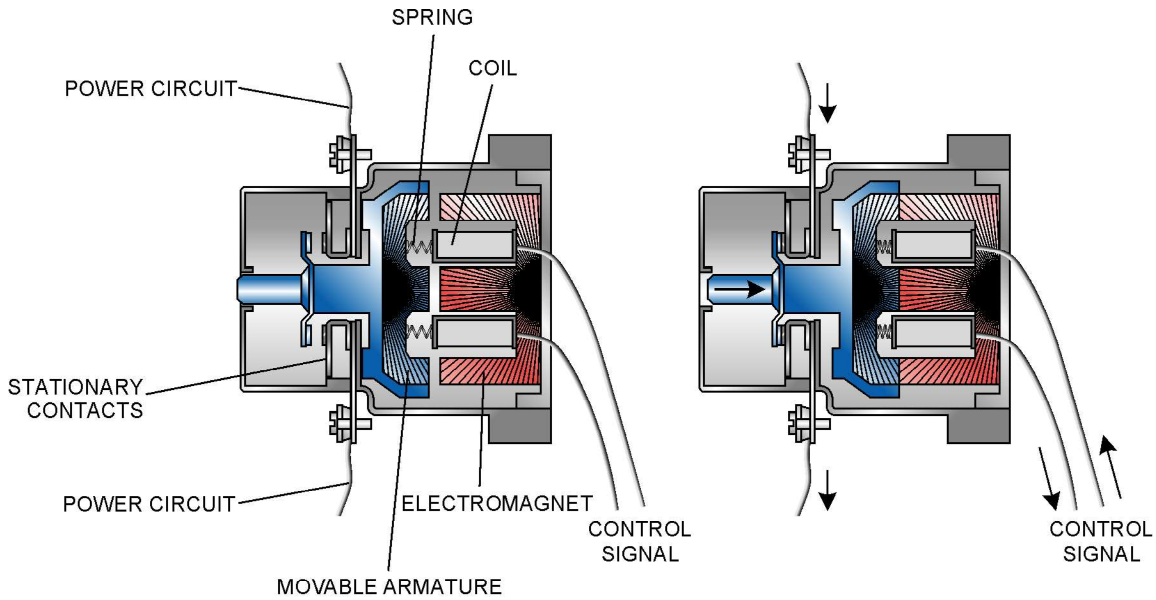


Figure 1-14. Single-pole solenoid-operated magnetic switch.

Contactors

Contactors are heavy-duty and use a small control current or manual switching to command power-consuming loads like motors, or lighting and heating devices. Contactors are similar to motor starters, except that they do not provide overload protection. Figure 1-15 shows the Contactor module, Model 3127. A1–A2 are the coil terminals. L1, L2, L3, T1, T2, T3 are the input and output power terminals. 13-14 is an auxiliary NO contact, used to provide feedback about the contactor state.

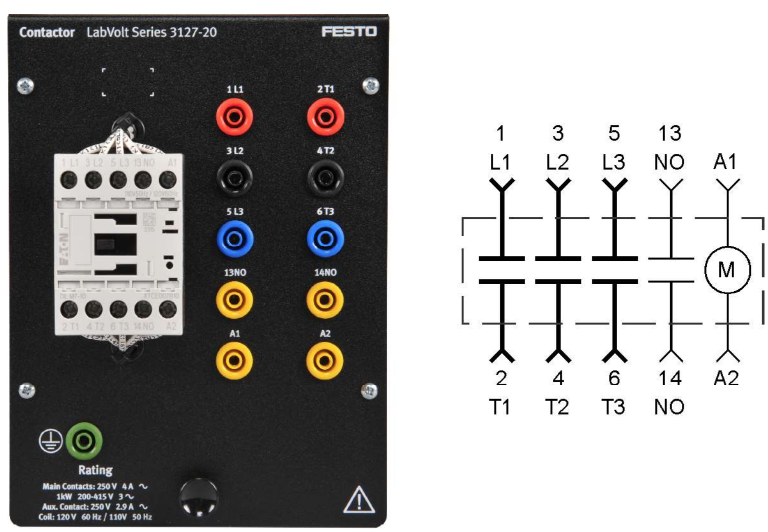


Figure 1-15. Contactor, Model 3127.

To reverse the direction of a motor, an arrangement of two contactors can be made, with each contactor dedicated to either forward or reverse direction. These contactors may then serve the same purpose as the Cam Switch module, except they are operated by way of external circuits.

Figure 1-16 shows the Dual Contactors module, Model 3119, made of two contactors similar to the one of Model 3127. Auxiliary blocks are added on top of the contactors to provide more feedback about the state of the contactors. The Dual Contactors module can be used to reverse the direction of rotation of a three-phase motor. A mechanical interlock is located between the two contactors. It is a safety mechanism, preventing the motor from being powered by the two contactors at the same time, thus preventing short-circuits from occurring. When one of the two contactors is energized, the contacts of the other contactor are mechanically maintained, even if the second coil is energized.

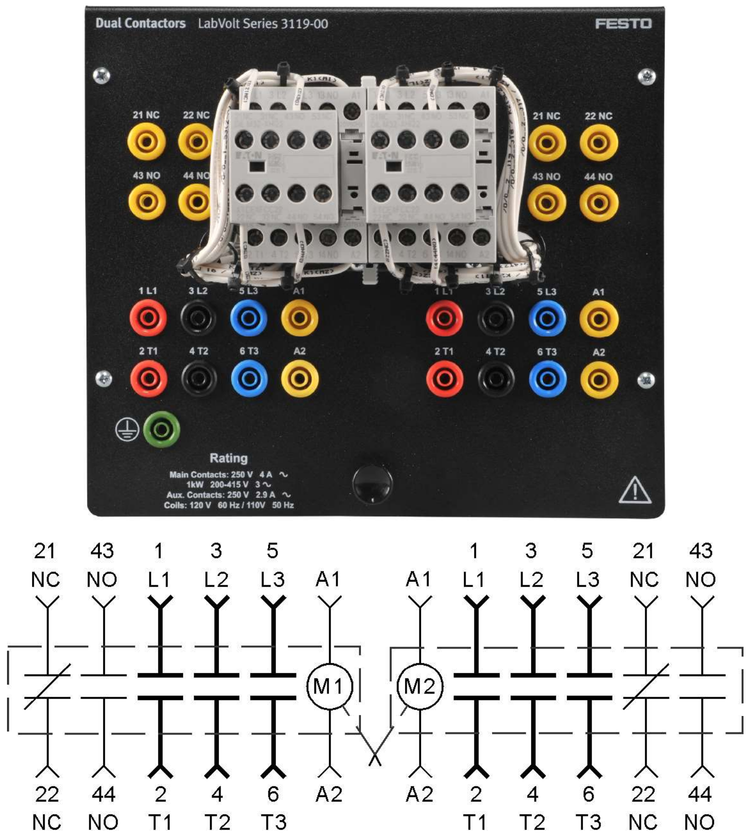


Figure 1-16. Dual Contactors, Model 3119.

Control relays

Control relays are designed to control circuits and small loads like pilot lights, audible alarms, and some small motors. Figure 1-17 shows the Control Relay module, Model 3130. A1–A2 are the coil terminals, 13–14 and 43–44 are NO contacts, while 21–22 and 31–32 are NC contacts.

Contact terminals ending with 1 or 2 are NC, while terminals ending with 3 or 4 are NO.

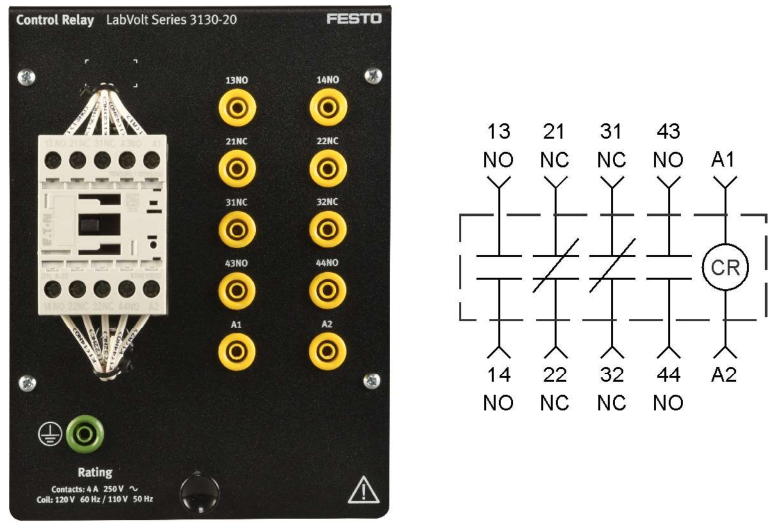


Figure 1-17. Control Relay, Model 3130.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Basic setup
- Contactor and control relay operation
- Dual contactors operation
- Mechanical interlock

PROCEDURE

In the first part of this exercise, you will inspect the Contactor and the Control Relay to identify their terminals and the voltage required to energize their coils.

In the second part of the exercise, you will connect a circuit containing a toggle switch and the Dual Contactors. This will help you fill out a target table that will show which power lines have been inverted between the two contactors.

In the last part of the exercise, you will set up a simpler dual contactor circuit to observe how the mechanical interlock operates.

⚠ WARNING

The AC Power Supply provides high voltages. Do not change any AC connection with the power on.

Basic setup

1. Perform the Basic Setup and Lockout/Tagout procedures.

Contactor and control relay operation

2. Examine the Contactor module, Model 3127. Choose from the following list the purpose of each of the different terminals:

   Coil – NC Contact – Mechanical Interlock – NO Contact – First Power Contact – Second Power Contact – Third Power Contact

   1L1 – 2T1: ____________

   3L2 – 4T2: ____________

   5L3 – 6T3: ____________

   13NO – 14NO: ____________

   A1 – A2: ____________

3. Is the auxiliary contact designed for power or control purposes?

   ❑ Power ❑ Control

4. What type of voltage is used to energize the coil?

   ❑ DC ❑ Single phase ❑ Three-phase

The black moveable plunger is located on the top of the contactor. You may press it with your finger to get a feel for its motion.

5. Examine the Control Relay module, Model 3130. Choose from the following list the purpose of each of the different terminals:

   Coil – NC Contact – Mechanical Interlock – NO Contact – First Power Contact – Second Power Contact – Third Power Contact

   13NO – 14NO: ____________

   21NC – 22NC: ____________

   31NC – 32NC: ____________

   43NO – 44NO: ____________

   A1 – A2: ____________

6. Does the Control Relay have power contacts?

❑ Yes ❑ No

7. What type of voltage is used to energize the coil?

❑ DC ❑ single phase ❑ three-phase

The black moveable plunger is located on the top of the control relay. You may press it with your finger to get a feel for its motion.

Dual contactors operation

8. Connect the circuit shown in Figure 1-18.

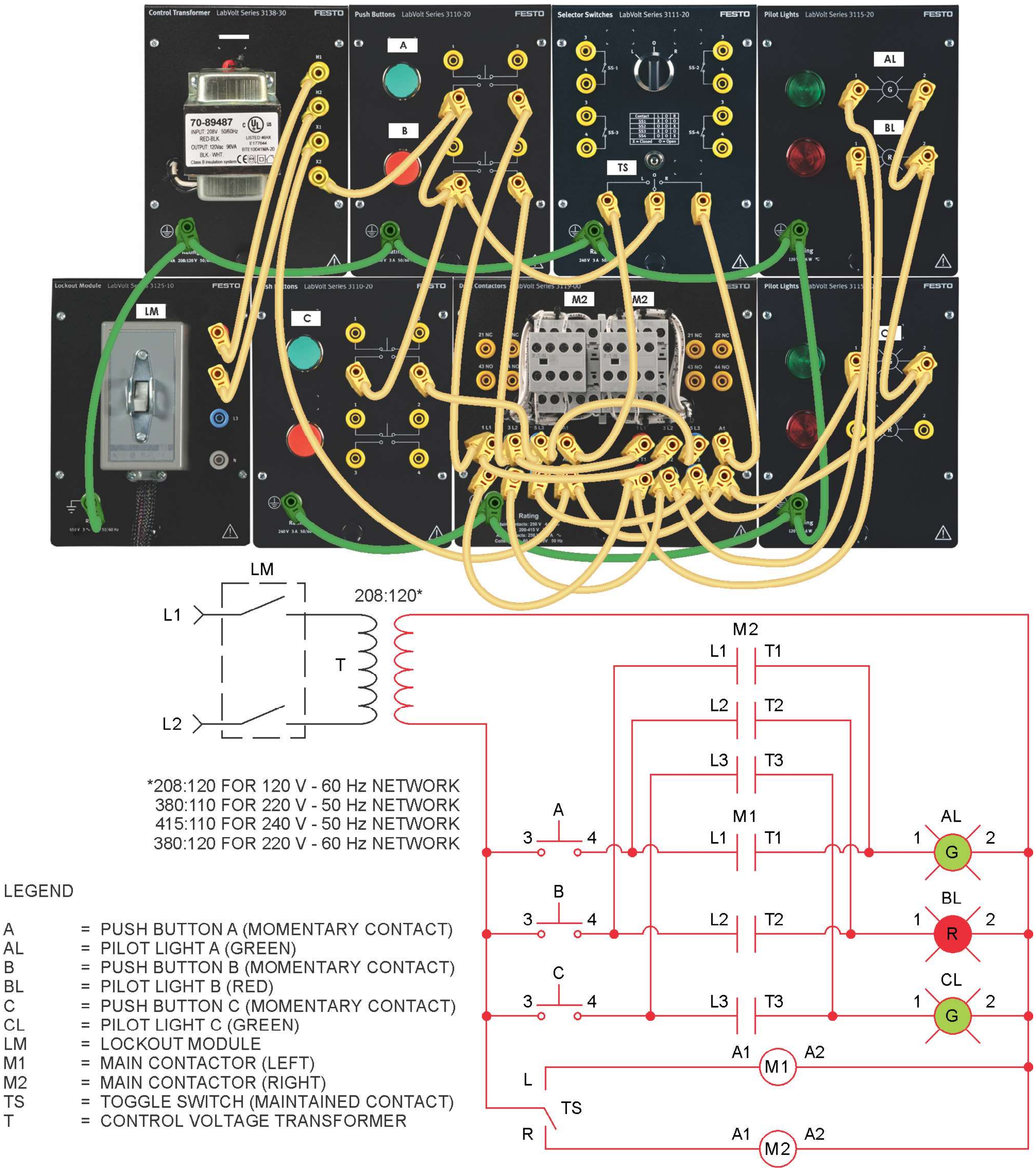


Figure 1-18. Dual contactors reversing circuit.

9. Set the TS toggle switch of the Selector Switches module to the O position.

10. Perform the Energizing procedure.

11. Set the TS toggle switch to the L and R positions to energize the coils M1 and M2 respectively.

Press all push buttons alternately, and fill out Table 1-4.

Table 1-4. Target table of the dual contactors reversing circuit.

Coil energized	Push button actuated	Pilot light illuminated		
		AL	BL	CL
M1	A			
	B			
	C			
M2	A			
	B			
	C			

12. According to Table 1-4, which lines have been interchanged?

❑ 1 and 2 ❑ 1 and 3 ❑ 2 and 3 ❑ None

13. Perform the Lockout/Tagout procedure.

Mechanical interlock

14. Connect the circuit shown in Figure 1-19.

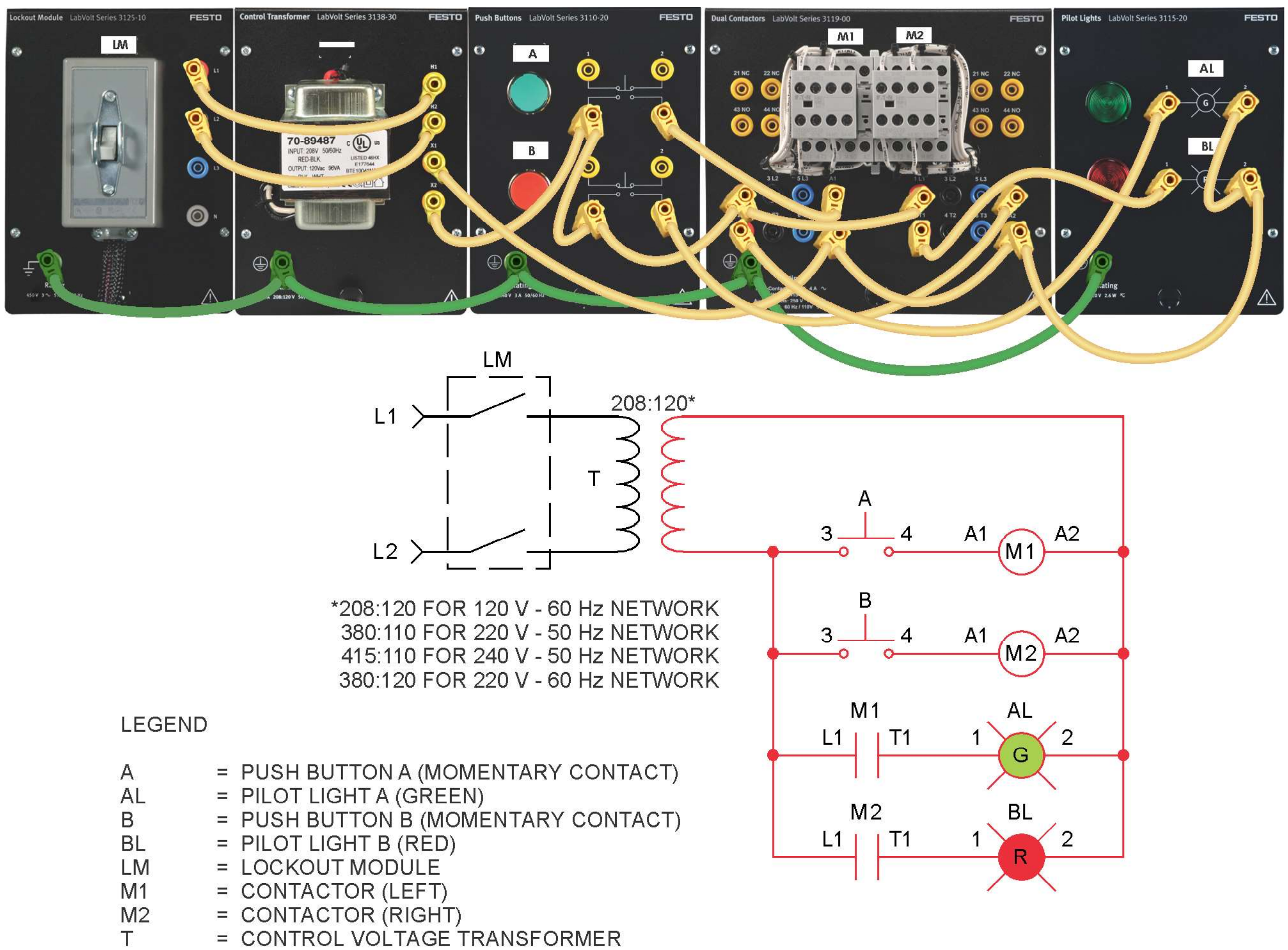


Figure 1-19. Mechanical interlock testing circuit.

15. Perform the Energizing procedure.

16. Which pilot light illuminates when you press the A push button?

❑ AL pilot light ❑ BL pilot light

17. Which pilot light illuminates when you press the B push button?

❑ AL pilot light ❑ BL pilot light

18. What do you observe and hear when you hold down the A push button and press the B push button momentarily?

19. What do you observe and hear when you hold down the B push button and press the A push button momentarily?

20. What mechanism between the contactors prevents both pilot lights from being powered simultaneously?

21. Turn the individual power switch of the AC Power Supply off, disconnect the circuit, remove the magnetic labels, and return the equipment to the storage location.

Conclusion

Solenoids are magnetic devices used to open and close contacts of contactors and control relays.

Contactors are switching devices designed for power circuits, while control relays are built for control circuits and small loads.

Dual contactors with a mechanical interlock allow reversing the rotation direction of a motor, without risking powering both coils at the same time.

Review Questions

1. What type of relays are used to switch electric power circuits?

   a. Control relays

   b. Contactors

   c. Buchholz relays

   d. Cam switches

2. What does the term "magnetic" refer to when talking about contactors?

   a. Presence of a solenoid controlling the contacts.

   b. Presence of a permanent magnet.

   c. Presence of a compass.

   d. Risk of being attracted by the device.

3. What is the purpose of auxiliary contact switches on motor starters?

   a. Switch power lines.

   b. Receive information from the PLC.

   c. Provide feedback about the motor condition.

   d. Connect a multimeter.

4. What is the name of the moving part, attracted by an energized coil, in a magnetic relay?

   a. Solenoid

   b. Plunger

   c. Contact

   d. Knob

5. What is the purpose of a mechanical interlock in dual contactors?

   a. Prevents both coils from being energized at the same time.

   b. Enables motor power boosting.

   c. Prevents motor overheating.

   d. Enables DOL starting.

Current Protection Devices

EXERCISE OBJECTIVE Describe and test the operation of circuit breakers, fuses, and overload relays.

DISCUSSION OUTLINE The Discussion of this exercise covers the following points:

- Circuit breakers
- Fuses
- Overload protection

DISCUSSION Motors can be damaged by excessive currents going through their windings. Protection devices must be added to motor circuits to prevent the machines from burning up.

Circuit breakers or fuses are necessary to avoid high current levels rushing into the motor windings. Under such conditions, these protection devices open the circuit immediately.

Low levels of excessive current may also cause damage to the motor over a certain period of time. Overload protection devices will open the circuit when the current drawn by the motor is relatively high after a time delay.

When sizing the protection devices, it is important to note that all electric motors suffer from a condition called **inrush current**. When starting the motor, there is a brief spike of current that can be several times the steady-state current. Protection devices must be carefully chosen so that they do not unnecessarily disrupt the system under those normal conditions.

Circuit breakers

Circuit breakers are switches that open the circuit automatically when a predetermined current level is exceeded. Circuit breakers can be reset to resume normal operation. Figure 1-20 shows three-phase circuit breakers.

Figure 1-20. Three-phase circuit breakers.

When electrical contacts open to interrupt a large current, there is a tendency for an arc to form between the contacts, which would allow the flow of current to continue. The maximum short-circuit current that a breaker can interrupt safely is called the **interrupting capacity**.

Fuses

A fuse protects the circuit from an overcurrent condition. Its metal alloy melts when heated by a prescribed electric current, hence opening the circuit. Fuses are classified by types which depend on the application. A fuse also has a rated interrupting capacity, which is the maximum current the fuse can safely interrupt. Figure 1-21 shows the Fuse Holder module, Model 3137.

Compared to circuit breakers, fuses have the advantage of being cheaper for similar ratings. However, blown fuses must be replaced with new devices, which is less convenient than simply resetting a breaker. In addition, when a single fuse blows in a three-phase system, the two other phases may still be operational, which is possibly hazardous. In comparison, a three-phase circuit breaker interrupts all phases simultaneously.

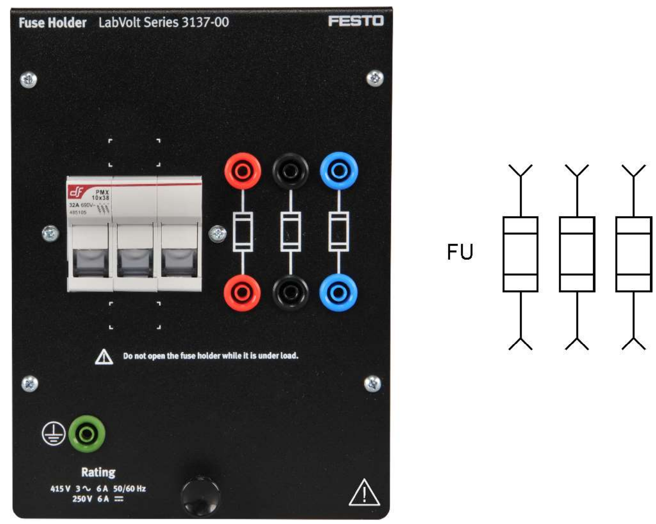


Figure 1-21. Fuse Holder, Model 3137.

Overload protection

Electric motor overload protection is necessary to prevent burnout and ensure maximum operating life of the motor. Motor overloads may be caused by:

- an undersized motor;
- increased load on the driven machine;
- low input voltage;
- numerous start/stop cycles;
- an open phase in a polyphase system.

When an overload occurs, the motor draws excessive current, causing overheating. Since the insulation of a motor breaks down under excessive heat, limits have been established for motor operating temperatures. Overload relays are used to limit the amount of current drawn to a predetermined value. These relays have current sensitive thermal or magnetic elements that de-energize the starter and stop the motor when excessive current is drawn. Local electrical codes determine the size and class of the overload relay.

The class number indicates how long the overload relay takes to trip when carrying a current equal to 6 times its current rating (or the value set when the overload is adjustable):

- Class 10 overload relay will trip in 10 seconds or less at a current equal to 6 times its rating.
- Class 20 overload relay will trip in 20 seconds or less at a current equal to 6 times its rating.
- Class 30 overload relay will trip in 30 seconds or less at a current equal to 6 times its rating.

Class 10 overload relays are usually used with motors that heat faster, such as hermetic motors, or submersible pumps. Class 30 overload relays are mostly used with motors driving high inertia loads, that take more time to accelerate.

Figure 1-22 shows the tripping time as a function of the ratio between the circuit actual current and the overload relay's current setting for different overload relay classes. This ratio is equal to the number of times by which the circuit actual current exceeds the overload relay's current setting.

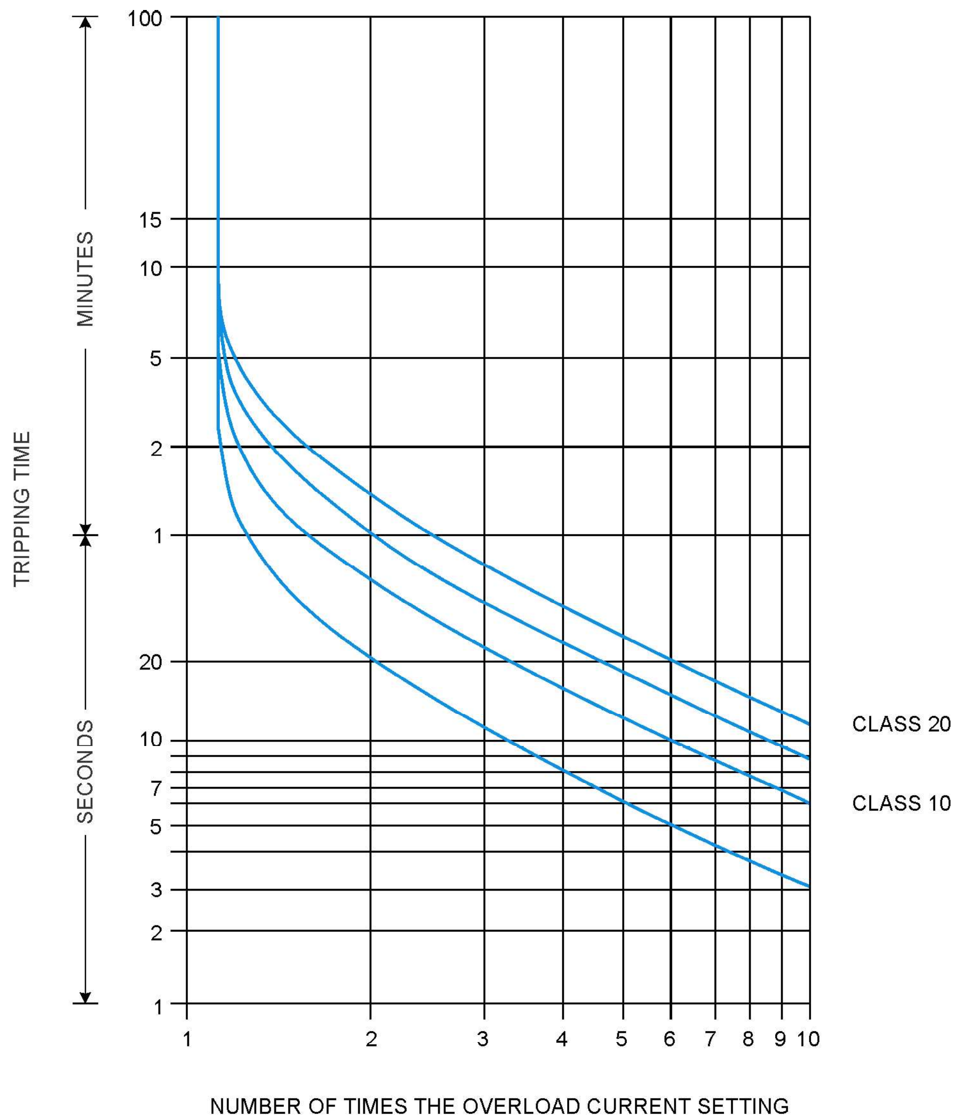


Figure 1-22. Overload classes tripping chart.

Figure 1-23 shows the Overload Relay module, Model 3131. This thermal overload device has adjustable tripping current. Figure 1-24 explains how this thermal overload relay operates. When the current level rises, the bimetal strips heat up and bend to **trigger** the auxiliary contacts. This action is more or less rapid, depending on the ambient temperature.

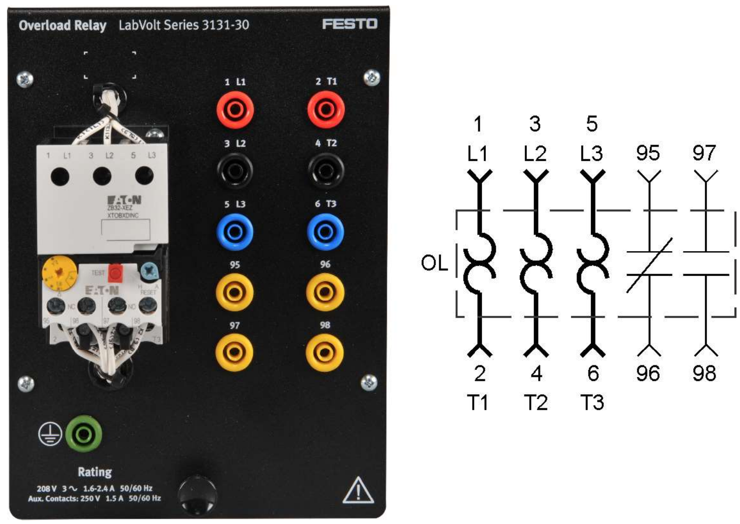


Figure 1-23. Overload Relay, Model 3131.

The auxiliary contacts (95–96 and 97–98) subsequently switch off the load by means of a contactor. The tripped status is signaled by means of a switch position indicator. The contactor is either reset manually (position H) or automatically (position A).

The test button on the Overload Relay module is for contacts testing. Pressing the test button opens the NC contact, and pulling the same test button closes the NO contact.

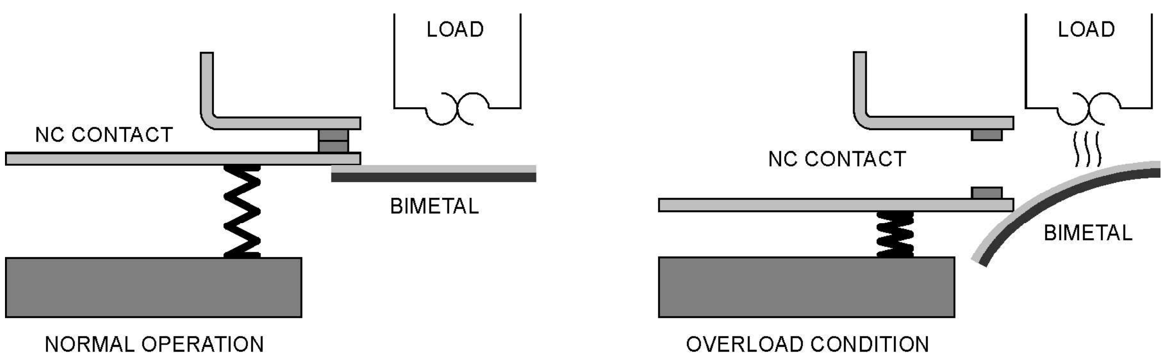


Figure 1-24. Bimetal overload operation.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Basic setup
- Overload protection using the manual starter
- Overload protection using the overload relay

PROCEDURE

In the first part of this exercise, you will set up a tripping circuit for the Manual Starter. You will first test the circuit breaker section of the Manual Starter by shorting the circuit. After that, you will intentionally overload the circuit to make the overload relay part trip.

In the second part of the exercise, you will use a tripping chart to identify the overload class and theoretical tripping time of the Overload Relay module. You will then implement a circuit with the Overload Relay module to verify the theoretical tripping time value. You will also see that heat has an effect on an overload relay tripping time.

Finally, you will compare the Manual Starter and the Overload Relay and observe that the first works directly on the power lines and the latter, on the control circuit.

⚠ WARNING

The AC Power Supply provides high voltages. Do not change any AC connection with the power on.

Basic setup

1. Perform the Basic Setup and Lockout/Tagout procedures.

Overload protection using the manual starter

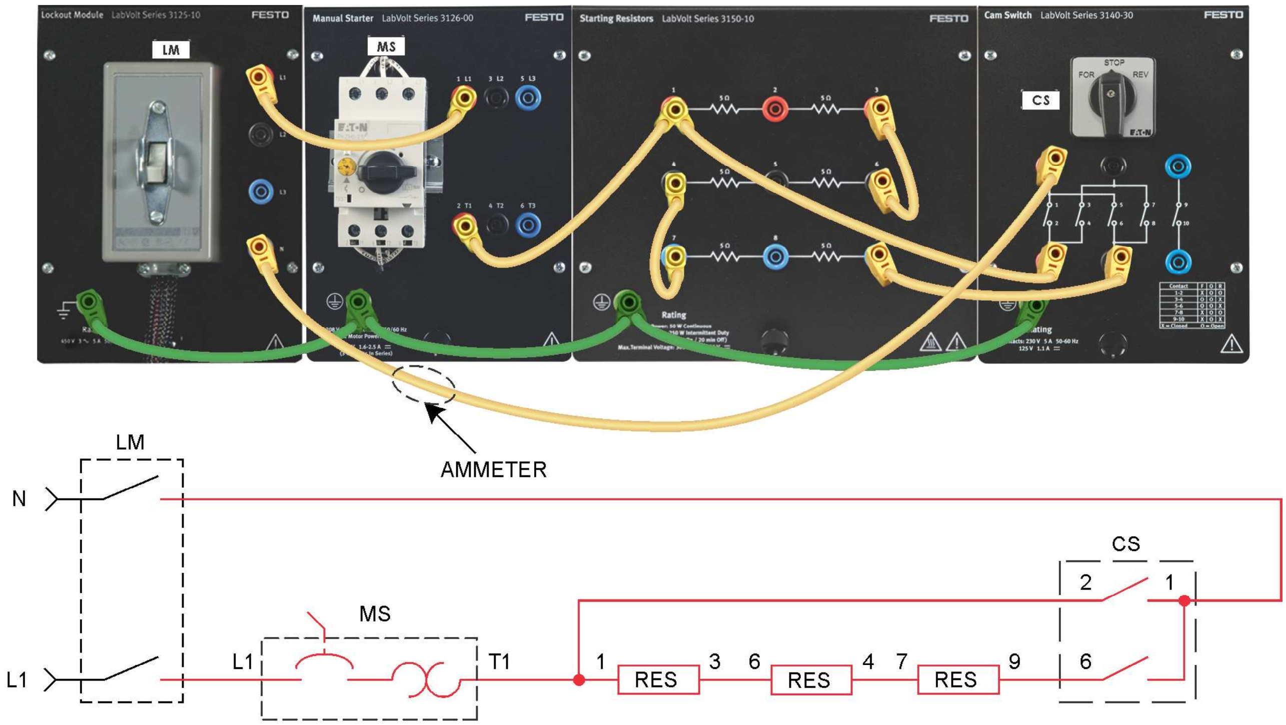
2. Connect the circuit shown in Figure 1-25.

3. Set the Cam Switch to the STOP position.

   Set the overload potentiometer of the Manual Starter to the lowest value, and the knob to the **I** position.

   Clamp an ammeter around a power lead as shown in Figure 1-25.

   Perform the Energizing procedure.



LEGEND

CS = CAM SWITCH
LM = LOCKOUT MODULE
MS = MANUAL STARTER (CIRCUIT BREAKER WITH OVERLOAD)
RES = RESISTOR

AC LINE VOLTAGE	VALUE OF R_{EQ} RESISTORS IN SERIES
120 V - 60 Hz	R_{EQ} = 10 Ω x 3 = 30 Ω
220 V - 50 Hz	R_{EQ} = 40 Ω x 3 = 120 Ω
240 V - 50 Hz	R_{EQ} = 40 Ω x 3 = 120 Ω
220 V - 60 Hz	R_{EQ} = 40 Ω x 3 = 120 Ω

Figure 1-25. Manual Starter tripping circuit.

4. Start the chronometer as you set the Cam Switch to the FORW (FDW) position.

   How long does it take for the Manual Starter overload to trip? Explain what happened.

   ____

   ____

   ____

5. Set the Cam Switch to the STOP position.

Reset the Manual Starter by turning the knob to the I position.

Start the chronometer as the Cam Switch is set to the REV position.

Referring to the ammeter display, what is the current flowing through the circuit?

Current:________

6. How long does it take for the Manual Starter overload to trip?

Tripping time:________

7. By how many times is the measured current higher than the Manual Starter's overload current setting?

Number of times (ratio): _______

8. Explain what happened compared to when the Cam Switch is set to the FORW (FDW) position.

____

____

____

CAUTION

The Starting Resistors module may be hot. Please be careful when you handle this module after use.

9. Perform the Lockout/Tagout procedure.

10. Referring to Figure 1-22, determine the overload class of the Manual Starter by using the tripping time and current ratio determined from the Figure 1-25 circuit.

❑ Class 10 ❑ Class 20 ❑ Class 30

11. Referring to Figure 1-22, at six times the overload relay's current setting, how long should the Manual Starter take to trip?

Tripping time: _______

Overload protection using the overload relay

12. In the Figure 1-26 circuit, what would happen in case of a short-circuit (if the only short-circuit protection device is the Fuse Holder)?

____

____

13. Calculate the current that will flow through line L3, using the nominal voltage, resistor value, and Ohm's law ($E = RI$).

Current: _____

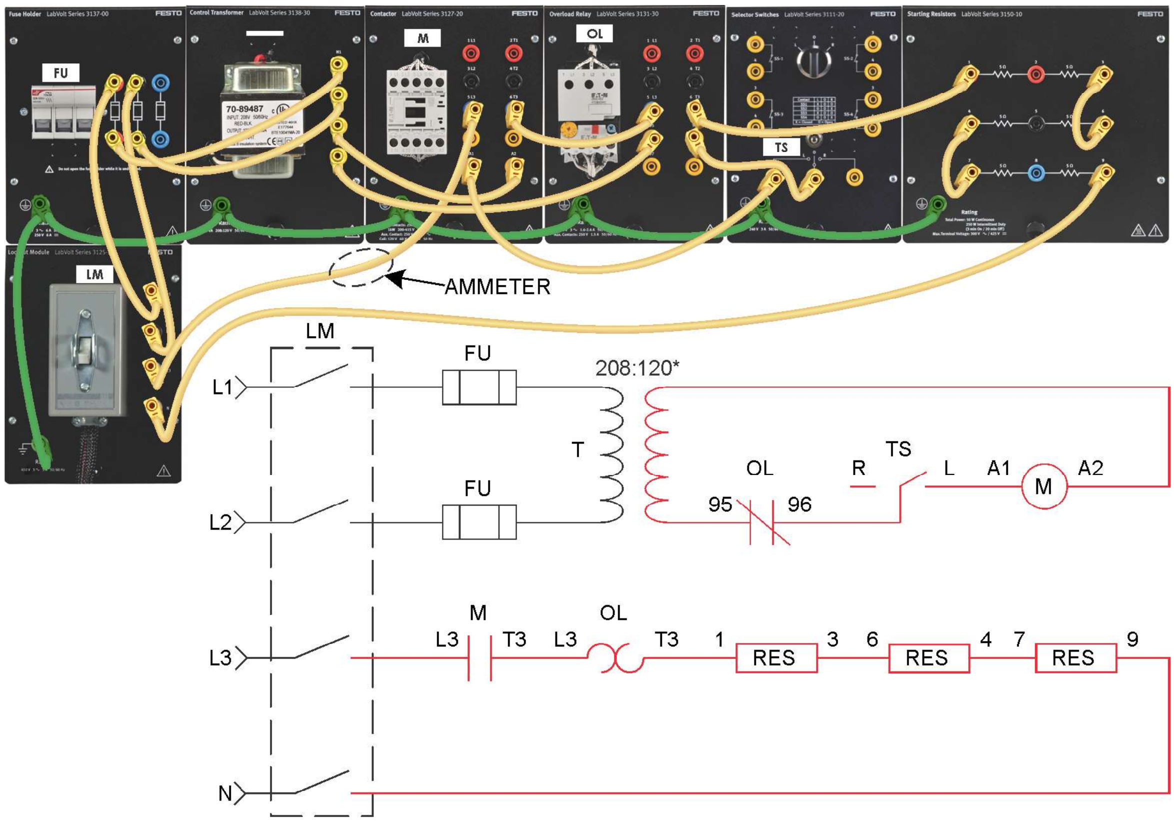
14. Calculate the ratio of the current calculated in the previous step to the Overload Relay's current setting (lowest value on the potentiometer) ($I_{CALCULATED} / I_{OVERLOAD}$).

Ratio: ______

15. Referring to Figure 1-22, how long should it take for the overload relay to trip, when power is applied to the circuit? Use the current ratio calculated in the previous step.

Tripping time: ________

16. Connect the circuit shown in Figure 1-26.



*208:120 FOR 120 V - 60 Hz NETWORK
380:110 FOR 220 V - 50 Hz NETWORK
415:110 FOR 240 V - 50 Hz NETWORK
380:120 FOR 220 V - 60 Hz NETWORK

AC LINE VOLTAGE	VALUE OF R_{EQ} RESISTORS IN SERIES
120 V - 60 Hz	R_{EQ} = 10 Ω x 3 = 30 Ω
220 V - 50 Hz	R_{EQ} = 40 Ω x 3 = 120 Ω
240 V - 50 Hz	R_{EQ} = 40 Ω x 3 = 120 Ω
220 V - 60 Hz	R_{EQ} = 40 Ω x 3 = 120 Ω

LEGEND

FU = FUSE
LM = LOCKOUT MODULE
M = MAIN CONTACTOR
OL = OVERLOAD RELAY
RES = RESISTOR
TS = TOGGLE SWITCH (MAINTAINED CONTACT)

Figure 1-26. Overload Relay tripping circuit.

17. Set the overload potentiometer of the Overload Relay to the lowest value, and the reset button to the A (automatic reset) position.

Set the TS toggle switch of the Selector Switches module to the O position.

Clamp an ammeter around power line 3 as shown in Figure 1-26.

Before installing the Fuse Holder module, make sure that the fuses inside are not blown.

Perform the Energizing procedure.

18. Start the chronometer as you set the TS toggle switch to the L position.

Referring to the ammeter display, what is the current flowing through the circuit?

Current: ______

19. How long does it take for the overload relay to trip?

Tripping time: ______

20. How long does the Overload Relay take to reset automatically (wait for the current to flow again)?

Reset time: ______

21. How long does it take for the overload relay to trip a second time?

Tripping time: ______

22. Compare the tripping time measured for the second reset (step 21) to the tripping time measured for the first reset (step 19). How was the tripping time measured for the second reset?

❑ Shorter ❑ Longer ❑ About the same

The bimetal strip inside the Overload Relay is still hot after the first reset.

23. Does the theoretical tripping time obtained with the chart correspond to the value obtained experimentally?

❑ Yes ❑ No

24. What reasons could explain a difference between calculated and experimental results?

____

____

____

25. Do the Manual Starter and the Overload Relay take nearly the same time to trip under similar conditions?

❑ Yes ❑ No

26. Which device works directly on the power lines?

❑ Manual Starter ❑ Overload Relay

27. Explain how the two devices make the motor stop.

____

____

____

____

28. Turn the individual power switch of the AC Power Supply off, disconnect the circuit, remove the magnetic labels, and return the equipment to the storage location.

CONCLUSION

Circuit breakers and fuses protect circuits from high current levels. They open the circuit if the current is between their rating and their interrupting capacity. Circuit breakers can be reset, while fuses have to be replaced after use.

Overload protection is used to prevent burnout of the motor. Overload relays limit the amount of current drawn to a predetermined value. The higher the current, the less time it takes to de-energize the contactor and stop the motor. Thermal overload relays heat up depending on the motor current.

REVIEW QUESTIONS

1. What condition **does not** cause a motor overload?

   a. An oversized motor.

   b. The loss of a phase in a polyphase system.

   c. A low voltage.

   d. A heavy load.

2. How do bimetallic overload relays operate?

   a. Sensors measure the strength of the magnetic field around the power line.

   b. Metal alloys melt as heat goes up with the current rise.

   c. Heat goes up as the current rises, causing bimetal strips to bend.

   d. Bimetal strips are actuated by radio-frequency signals.

3. What is the main difference between circuit breakers and fuses?

   a. Fuses may be reset, circuit breakers have to be replaced.

   b. Fuses open circuits when the current is too high.

   c. Circuit breakers open circuits when the current is too high.

   d. Fuses have to be replaced; circuit breakers may be reset.

4. What is the class of a 6 A overload, if it trips in 20 seconds at a current of 36 A?

   a. Class 10

   b. Class 20

   c. Class 30

   d. Class 40

5. What is a motor inrush current?

   a. The current drawn by a motor at steady state.

   b. A brief spike of current when the motor is starting.

   c. The current that is converted into heat.

   d. The current that is converted into motion.

Unit Test

1. Who must be advised that a lockout/tagout procedure is going to be performed?

   a. The maintenance department workers only.
   b. The foreman only.
   c. All affected employees.
   d. All employees of the company.

2. What has to be done before lockout/tagout procedures can be implemented?

   a. Identification of hazards to which workers can be exposed.
   b. Collection of information coming from a sufficient number of accidents.
   c. Wait for the government to ask the company to carry out such procedures.
   d. All of the answers above are correct.

3. Which devices may be used to reverse the sequence of three-phase power lines?

   a. Toggle switch and pilot light.
   b. Selector switch and control relay.
   c. Push button and emergency button.
   d. Cam switch and dual contactors.

4. What is the name of the coil of wire around a soft iron core used to operate magnetic contactors and relays?

   a. Lever
   b. Plunger
   c. Solenoid
   d. Drum

5. What are the two essential components of a magnetic motor starter?

   a. Auxiliary contacts and overloads.
   b. Pilot lights and auxiliary contacts.
   c. Contactors and pilot lights.
   d. Contactors and overloads.

6. What is the name of the highest current that a device can interrupt at a rated voltage?

   a. Interrupting current
   b. Excessive current
   c. Overload current
   d. High-level current

7. What components offer protection against a sustained low level of excessive current?

   a. Fuses
   b. Overload relays
   c. Circuit breakers
   d. Solenoids

8. What phenomenon happens immediately after full voltage is applied to start a motor?

   a. Full-load current
   b. Pressure overload
   c. Mechanical overload
   d. Inrush current

9. Which of the following control devices does not hold its state?

   a. Cam switch
   b. Selector switch
   c. Toggle switch
   d. Push button

10. What device is designed to stop the equipment rapidly and easily?

    a. Pilot light
    b. Emergency button
    c. Cam switch
    d. Overload relay