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Motor Control Part 1
The Basics of Protection and Control

by

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Introduction

Electric motors were invented in the 19th century and played a major role in the 2nd industrial revolution. They have been used to drive all types of equipment in both residential and industrial applications. They can be found in residential and commercial buildings, manufacturing plants, process industries and many other applications. Understanding the basics of electrical motors and motor starters has value for many engineering and architectural disciplines. This course is intended to teach:

1. Basics of AC induction motors
2. The purpose and function of a motor starter
3. Components of motor starter power circuits
4. Basics of motor control

Motors can be divided into two major types - AC and DC. AC motors can be classified as synchronous and asynchronous. Asynchronous AC induction motors are the most common type of motor. This training will focus on starting low voltage (<1000 VAC), three-phase asynchronous motors.

A few notes about agencies and organizations involved in the design and use of electrical equipment which are mentioned in the training:

NEMA is the National Electrical Manufacturers Association. NEMA establishes standards for the operating performance, characteristics, construction and testing to ensure standardization of electrical equipment.

IEC is the International Electrotechnical Commission which is an international organization which publishes standards for electrical equipment.

The National Electric Code (NEC) is one of the codes published by the National Fire Protection Association (NFPA). This is the code adopted by each state to establish safe practices of electrical design, installation, and inspection to protect people and equipment from electrical hazards.

AC Induction Motors

An AC electric induction motor is made up of two main components, the rotor and the stator. Both are made of loops or coils of conductors. When electric current flows through coils, an electromagnetic field is created around the coils. It is this principle, along with the interaction between the coils of the rotor and stator, that allow induction motors to operate.

When AC current flows in the stator, it creates a rotating electromagnetic field that produces a rotating force (torque) on the rotor. This rotating force causes the motor shaft to rotate. The speed of the motor depends on the construction and number of the stator coils, described as "poles" and the power system frequency. The actual speed of the motor will be slightly slower than the synchronous speed of the electromagnetic field. This difference between the synchronous speed and the actual speed is called "slip". The slip for the most common NEMA design motor is 3-5% of the synchronous speed.

When discussing AC induction motors, it is common to refer to them by their synchronous speed even though they actually operate slightly slower. The synchronous speed of a motor can be calculated using the following formula:

$$Sync\ Speed\ (RPM) = System\ Frequency\ (Hz) * 60/(\frac{\#\ of\ poles}{2})$$

The speed that the motor turns when driving the rated load at rated voltage is the full load speed that will be stamped on the nameplate. A common motor design is a 4-pole motor, which will have a synchronous speed of 1800 RPM and a full load rated speed of approximately 1750 RPM. Table 1 shows the synchronous speeds for various motor designs at 50 and 60 Hz.

Table 1: Motor Synchronous Speed

	Synchronous Speed (RPM)	
# of Poles	60 Hz	50 Hz
2	3600	3000
4	1800	1500
6	1200	1000

When designing a motor starter circuit, the motor nameplate will provide information that will be used as the basis for the design, component selection and settings. A typical nameplate is shown in figure 1. Some of the key information is motor power rating (HP or kW), motor voltage, full load amps (FLA) and service factor (SF).

Manufacturer's Name			
Cat. No	XYZ		
HP	7.5		
Enclosure	TEFC		
Volts	230/460		
Hz	60	Phase	3
Amps	18.8/9.5		
RPM	1770		
S.F.	1.15	Code	J
Nom Eff	91.6	P.F	82
Rating	40C Amb-Cont		

Figure 1: Typical Motor Nameplate Information

Purpose of Motor Starters

The purpose of a motor starter is to control the flow of electricity to the motor and provide protection for the motor against overload conditions. A motor starter is composed of a contactor to control the flow of electricity to the motor, and an overload relay to provide overload protection.

The term motor starter means the contactor and overload relay. This training will expand the discussion to include the disconnect and short circuit components, which when added to a motor starter are called a combination motor starter, sometimes referred to as a “combo starter”. The disconnect in a combination motor starter may or may not include a short circuit protection device.

Methods for Starting AC Induction Motors

There are several methods for starting motors:

1. Full Voltage Non-Reversing (FVNR) or Direct On-Line (DOL)
2. Full Voltage Reversing (FVR)
3. Wye-Delta or Star-Delta
4. Autotransformer
5. Solid State Reduced Voltage (SSRV)
6. Variable Speed Drives (VFD) or Adjustable Speed Drives (ASD)

This training will focus on full-voltage non-reversing starter functionality, circuit design and component selections for AC induction motors. Training for other starting methods will be provided in future courses.

Contactors

Full-voltage motor starters for AC motors can be divided into two types: manual starters and magnetic starters.

As implied by the name, a manual motor starter (MMS) relies on manually operating a pilot device that has a direct mechanical linkage that operates the contactor. The manual motor starter also provides short circuit and overload protection for the motor.

Magnetic starters consist of a contactor which operates by the magnetic field created when electrical current flows through a coil. When electricity flows through the coil, the coil is energized creating magnetic forces which close the contacts allowing power to flow to the motor. As long as current flows through the coil, the contactor remains closed and power flows to the motor. The motor stops when the current to the coil is removed, deenergizing the coil. When this happens a spring in the contactor pushes the contacts open and stops power flow to the motor.

In a magnetic motor starter there are two circuits, the power circuit and the control circuit. The power circuit is the circuit providing current to the motor. The control circuit is the wiring that interfaces the pilot devices or sensors to the control elements (contactor coils, pilot lights etc.).

Separating these circuits allows you to use low voltage wiring for the control circuit regardless of the motor voltage.

A contactor has three contacts for the power circuit and additional contacts for the control circuit which are called auxiliary contacts. Auxiliary contacts may be normally open or normally closed. The normally open contacts are identified by the letter “a”, and the normally closed contacts are identified by the letter “b”. This identification indicates their status when the contactor is deenergized. An “a” contact will be open when the contactor is deenergized and the motor is OFF. When the contactor is energized, the “a” contact will be closed, indicating that the motor is ON. The “b” contact is closed when the contactor is deenergized and open when the contactor is energized. A motor starter contactor will have at least one “a” aux contact and can have additional aux contacts added.

A drawing of a motor starter contactor may be shown with the power circuit terminals and the control circuit terminals, as shown in figure 2. The contacts for the power circuit are shown with terminals L1-3 on the line side and terminals T1-3 on the load side. The aux contacts are identified as Ma and Mb. The letter M indicates that these contacts are associated with the coil “M” on the contactor.

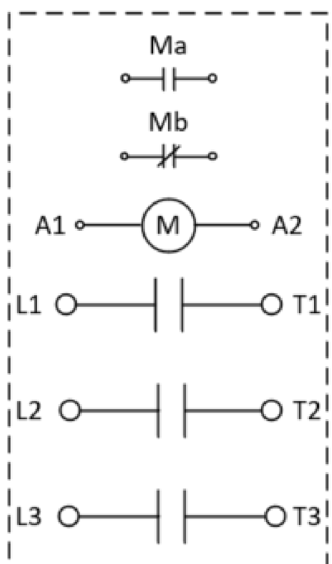

Figure 2: Contactor Terminal Identification

Contactors rated for motor loads have special characteristics to allow them to be used in motor starters. When an induction motor starts, the current can rise to 6-8 times the nameplate FLA. Some premium efficiency motors will have starting currents that can be 10-12 times the motor FLA. As the motor speed increases to the rated speed, the current will drop down to the nameplate current rating. The contactors rated for use in motor circuits must be rated to carry the FLA continuously and they must be able to carry the much higher starting currents. General purpose contactors and relay are no required to carry the high starting currents that motors require.

NEMA defines the characteristics and features of magnetic contactors for starters under a standardized system. These are referred to by their NEMA size. Table 2 shows the maximum HP rating for NEMA starter sizes 00 to 7.

Table 2: NEMA Motor Starter Ratings

NEMA Size	Continuous Current rating (A)	Maximum HP at 230VAC	Maximum HP at 460VAC
00	9	1.5	2
0	18	3	5
1	27	7.5	10
2	45	15	25
3	90	35	50
4	135	50	100
5	270	100	200
6	540	200	400
7	810	300	600

The NEMA ratings are more conservative than IEC contactor ratings and are generally more expensive than their IEC equivalent. Catalog data for IEC rated contactors includes data for motor starting and non-motor starting applications.

IEC rated contactors have ratings for utilization categories, called AC1, AC3 and AC4. Category AC1 applies to resistive loads and are not suitable for motor loads. Switching this type of load is easy with minimal arcing and electrical stress. Category AC3 applies to inductive motor loads for starting and stopping motors when the motor is up to full speed. Switching AC3 loads is much more stressful on the contactor than AC1 and the contactor must be able to withstand the higher starting currents.

The AC4 IEC rating is the most stressful on contactors. AC4 is a rating for rapid starting and stopping of motors (jogging). Rapid stopping of the motor just after starting means that the contactor must open when the current is higher than the motor FLA. This could mean opening the contactor when the current is 6 times the motor FLA. A high number of jogging operations will reduce the life of a contactor.

Table 3 shows typical catalog data for IEC rated contactors that can be used for starting motors up to 20 HP. The difference between the AC3 rating and the AC1 rating reflects the higher demand on contactors for motor starting applications.

Table 3:IEC Contactor Product Data

Contactor	Continuous Current Ratings (A)	Resistive Load AC-1 (A)	Inductive Load AC-3 (A)	Max HP at 460VAC
Contactor_09	25	20	9	5
Contactor_12	25	25	12	7.5
Contactor_18	32	32	18	10
Contactor_25	40	40	25	15
Contactor_32	50	50	32	20
Contactor_38	50	50	38	20
Contactor_40	60	60	40	30

Control Wiring

There are two common types of control wiring, “two-wire” control and “three-wire” control.

A two-wire control circuit shown in figure 3, require the START signal to be a maintained contact. This can be a maintained pushbutton, limit switch, float switch, logic controller or other sensing device. When the motor is started, current flows through the starting device to the contactor coil (M). Current continues to flow through both devices until the motor is turned off.

If utility power is lost, this type of control circuit will allow the motor to restart automatically, when power is restored. This should be considered as a possible safety issue depending on the type of machine the motor is driving.

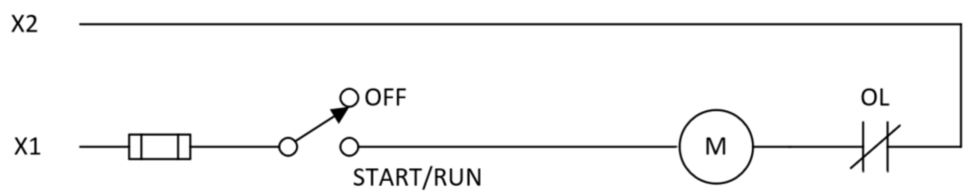

Figure 3: Two-Wire Control Circuit

In a three-wire control circuit shown in figure 4, the START signal can be a momentary contact. This can be a pushbutton, limit switch, float switch, logic controller or other sensing device. When the motor is started, current flows through the starting device to the contactor coil (M). A normally open auxiliary contact (Ma) on the contactor coil is wired in parallel with the START switch. When the contactor closes, the aux contact Ma will also close. Current will flow through the aux contact to the coil, keeping it energized. This is called the "seal-in" circuit. Having this circuit allows the starting switch to be released and current only flows through the seal-in circuit and contactor coil and the current does not flow through the starting switch.

If utility power is lost, this type of control circuit will not automatically restart the motor when power is restored. To restart the motor, the START push button will need to be pushed.

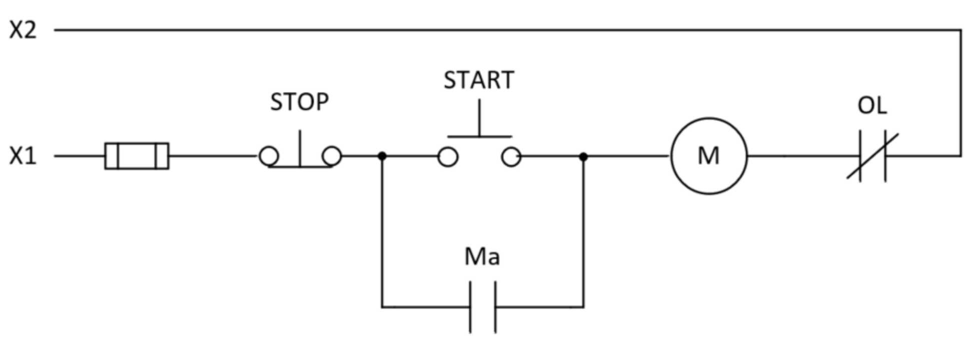

Figure 4: Three-Wire Control Circuit

Overload Relays

Now that we have a contactor and control circuit to start and stop power flow to the motor, we need to protect the motor. For the motor starter, this means motor overload protection. An overload occurs when the current drawn by the motor exceeds the full load amps (FLA) of the motor. Protection against high current is required because higher currents cause an increase in temperature in the motor. High motor temperatures are one of the causes of motor failure because the high temperatures can cause insulation failures in the electrical wiring.

During discussions of overload protection, the issue of concern is a load on the motor that is larger than the nameplate power rating. In our motor nameplate example in figure 1, the motor will draw the full load current of 9.5 amps when the motor load is 7.5 HP and the voltage is 460 VAC. When the load increases above 7.5 HP, the current will increase. There are other conditions that can cause the motor current to increase, such as voltage that is lower than the rated voltage. If the voltage decreases 10% from the motor rated voltage, the current will increase by 10%. The motor overload protection should protect the motor against high current caused by low voltage as well as loads that are higher than the motor rated power.

The amount of current increase during an overload will depend on the magnitude of the load compared to the motor rated power. Motor overload relays operate on an inverse-time characteristic that causes the relay to trip in a shorter amount of time when the current is higher. Motor overload relays have a trip class associated with them. The trip class is the number of seconds delay in the tripping function when the motor current is 600% of the current setting. Common trip classes are class 5, 10, 20 and 30. Class 20 is a common trip class for general purpose applications. Class 20 is the common class for starters in the NEMA starter size classification. Class 10 has become more common in the USA with the adoption of IEC motor starters. (See figure 5)

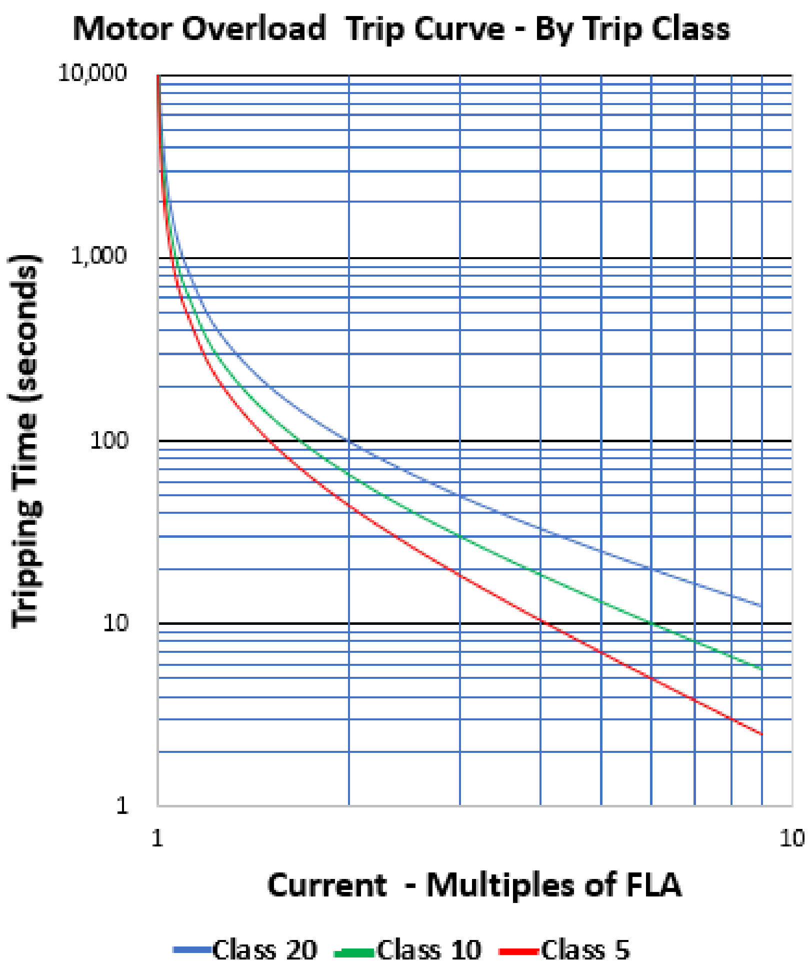

Figure 5: Tripping Class time-current curves

Types of Overload Relays

There are 3 types of motor overload relays: melting alloy, bimetallic and electronic.

A melting alloy motor overload relay uses a spring-loaded lever that is held in place by a metallic alloy. When heat from the motor current reaches a certain level, the alloy melts, releasing the lever to operate the relay by opening the overload contacts (OL) in the control circuit. This type of motor overload relay requires a manual reset to be able to restart the motor after it has cooled. These melting alloy elements are called heaters and are sized according the motor full load amps (FLA) and are purchased separately from the overload relay. To change the current trip setting for a melting alloy overload relay requires purchasing different heater elements.

A bimetallic motor overload relay uses a strip of 2 dissimilar metals bonded together to measure the heating effect of excess motor current. Because the two metals have different coefficients of expansion, as the temperature increases, one metal expands more than the other causing the bimetallic strip to bend. As the heat builds, the bimetal strip bends farther, until it engages the trip function of the overload relay, opening the overload contacts (OL) in the control circuit. Bimetallic overload relays typically have an adjustment dial that allow you to change the current setting from the lowest setting to 1.4 - 1.6 times the lowest setting. Bimetallic overloads have a fixed tripping class, are ambient compensated and include phase loss protection.

Electronic motor overload relays use current transformers to measure the magnitude of the motor current. The relay then uses an electronic model of motor heating to determine when the motor should be tripped. The use of electronics allows for a wider range of current setting as compared to bimetallic overload relays. Typical settings range from the lowest current setting to 5 times the lowest current setting. The trip class is selectable between class 10, 20 or 30 by a switch on the front of the unit. Electronic overloads are ambient compensated and include phase loss protection.

There is a family of advanced electronic motor management systems that provide electronic overload protection as described above and additional features. They can monitor voltage which along with the current measurements allow them to provide power information such as kW, kWH, power factor, etc. They can have additional inputs and outputs to have direct connections to the driven equipment or processes. As a motor management system, they have some basic logic processing capabilities to use the additional I/O for on-board programmable control functions. These advanced systems have communication capabilities to connect to a higher-level automation system. Communication systems will be serial protocols or ethernet based protocols. The advanced electronic processing can allow these systems to provide additional information and diagnostics to the automation system such as pending trip conditions and early warning about abnormal conditions in the machine or process.

Motor Circuit Disconnects

Article 430 of the National Electric Code (NEC) requires a disconnecting means be installed within site of the controller and motor. Disconnects can be a motor circuit switch rated in HP, molded case switch, molded case circuit breaker (thermal-magnetic), instantaneous circuit breaker, self-protected combination controller or manual motor controller. For individual motor circuits, the NEC states that the disconnect shall not be less than 115% of the motor full load current.

A motor circuit switch is a disconnect switch that has a horsepower rating. You may find these listed in catalogs under the heading of “safety switches”. These can be fused or unfused and will have a horsepower rating in the catalog for ease of selection. The non-fused switches will have a single maximum horsepower rating for a given voltage application. The fused switches will have separate ratings for a given voltage depending on the fuse type selection, which can be a fast-acting or dual-element time-delay fuse.

Molded case switches, molded case circuit breakers (MCCB), and instantaneous circuit breakers will look very similar, however they differ in the type of protection that they provide. A molded case switch is a means of disconnect only, with no protective features. A molded-case circuit breaker (thermal-magnetic) provides thermal protection against overloads and instantaneous (magnetic) protection against short circuits. An instantaneous circuit breaker, also called a motor circuit protector (MCP) provides instantaneous protection against short circuits. This is the same as the MCCB without the thermal protection.

Providing instantaneous-only protection by selecting a disconnect with fast-acting fuses or selecting an instantaneous circuit breaker is allowed by the NEC because overload protection is provided by the motor controller overload relay.

Motor circuit protectors are the most common disconnect and short circuit protection device for individual motor combination starters because they have an adjustable setting for the instantaneous feature and are easily resettable after a trip operation. Selecting an MCP for a motor circuit is aided by selection charts in manufacturer’s catalogs, based on the motor amps. The MCP will have a dial setting to set the motor FLA and a dial to adjust the instantaneous trip setting. In the example of our 7.5 HP motor with 9.5 amps, a typical MCP for this application will have a trip setting from 9 – 325A. The instantaneous setting needs to be set high enough so that it does not trip during the high starting currents, but not so high that it does not provide adequate protection. The maximum setting for an instantaneous trip circuit breaker is defined in NEC table 430.52 based on the specific motor design.

Figure 6 shows the settings for a 30 amp MCP with a current sensor rating of 30 amps. This can be used for motors with FLA of 1.5 to 25 amps. In our 7.5 HP motor example, the motor FLA is 9.5 amps and falls between two dial settings, 8 and 11 amps. When this happens, the dial can be set at either setting, then the instantaneous dial can be set at any of the settings as long as it does not exceed the maximum value in NEC table 430.52.

For a premium efficiency design B motor, the maximum limit in NEC table 430.52 is 1100%. For an FLA of 9.5 amps the maximum setting is 104.5 amps. Figure 6 shows the highest possible setting is using a motor FLA setting of 8 amps and an instantaneous setting of 13x. Another option is a motor FLA setting of 11 amps and an instantaneous setting of 9x.

	Current Im Setting	6x	8x	9x	10x	11x	12x	13x
	NEMA Motor FLA Setting	(FLA) * Insantaneous Setting						
Motor FLA	1.5	9	12	13.5	15	16.5	18	19.5
	3	18	24	27	30	33	36	39
	6	36	48	54	60	66	72	78
	8	48	64	72	80	88	96	104
	11	66	88	99	110	121	132	143
	14	84	112	126	140	154	168	182
	17	102	136	153	170	187	204	221
	20	120	160	180	200	220	240	260
	25	150	200	225	250	275	300	325

Figure 6: MCP Settings

Bringing it Together

We now have the components for a motor power circuit:

- Circuit Disconnect
- Short Circuit Protection
- Motor Contactor

- Overload Relay

We also have the components for a motor control circuit:

- Push Button / Switch
- Contactor Coil
- Contactor Auxiliary Contacts
- Overload Contact

The complete electrical drawing for a magnetic starter using three-wire control is shown in figure 7. This circuit shows the disconnect (MCP), motor starter contactor and coil (M) and overload (OL). The START/STOP push buttons, contactor auxiliary contact (Ma) and the overload contact (OL) are shown in the control circuit.

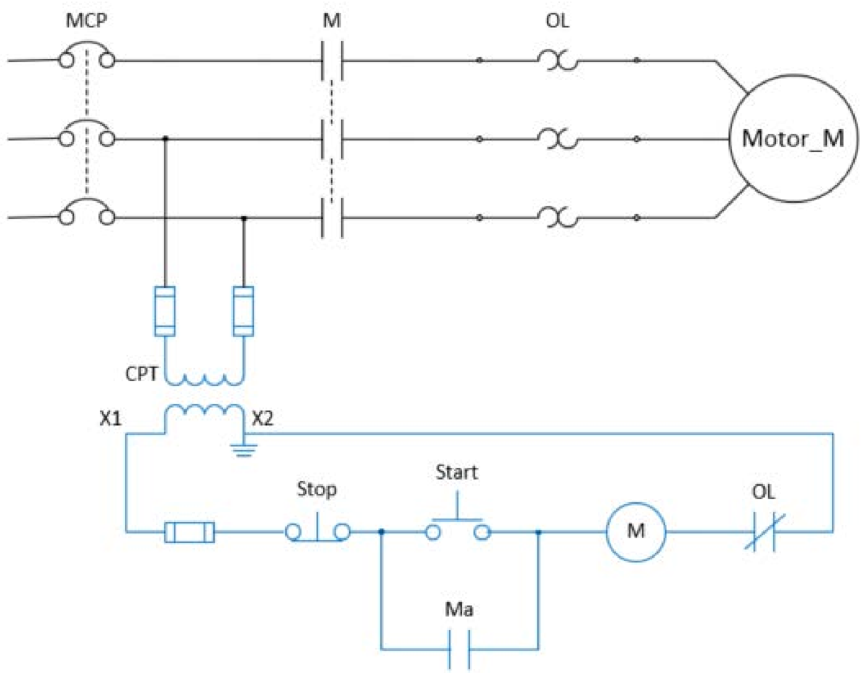

Figure 7: Power Circuit (black), Control Circuit (blue)

The references to specific NEC sections and tables are intended to be indicative of information required by the National Electric Code. This training does not address the full variety of motor applications that you may encounter. If you are designing motor circuits, selecting products or settings for motor protection and control, you are encouraged to get additional in-depth training on the National Electric Code for more details.