A SunCam online continuing education course

Electrical Power Distribution: Part 2
Drawings, Symbols & Studies

by

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Learning Objectives

This continuing education course is intended to provide training and education about the following topics:

1. Types of electrical engineering drawings used in project development, construction, and system maintenance
2. Information that can be found on electrical engineering drawings
3. Symbols and notes used on electrical engineering drawings
4. Types of electrical engineering studies, their purposes and uses

Introduction

Engineering documentation comes in many forms such as plans, drawings, specifications, data sheets, brochures, data sheets, and the results of engineering studies. This course is an introduction to the information that is commonly found on electrical engineering drawings, the symbols used to represent the equipment, and the information and purposes of some of the more common electrical engineering studies.

As an introductory-level course, it is good to be aware of the organizations that influence and govern codes and standards for the design, installation, and use of electrical equipment. Following is a list of organizations and institutions engaged in setting standards and codes that govern the design, manufacturing, installation, and/or testing of electrical equipment. The codes and standards from these organizations are commonly referenced on electrical engineering plans and specifications.

IEEE – The Institute of Electrical and Electronic Engineers is a non-profit professional association. The IEEE produces a wide range of publications which include consensus-based standards.

ANSI – The American National Standards Institute oversees standards and conformity assessment activities in the United States. ANSI facilitates and promotes voluntary consensus standards, conformity assessment systems, and safeguards their integrity.

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

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

NFPA – The National Fire Protection Association is a global nonprofit organization devoted to eliminating death, injury, and property or economic loss due to fire, electrical and related hazards. They deliver information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach, and advocacy.

NFPA 70 – One of the codes published by the NFPA and is the benchmark for safe electrical design, installation, and inspection to protect people and property from electrical hazards. This is also known as the National Electric Code.

NFPA 70E – One of the codes published by the NFPA that establishes requirements for safe work practices to protect personnel by reducing exposure to major electrical hazards. Originally developed at OSHA's request, NFPA 70E helps companies and employees avoid workplace injuries and fatalities due to shock, electrocution, arc flash and arc blast, and assists in complying with OSHA 1910 Subpart S and OSHA 1926 Subpart K.

Types of Drawings

Single-line diagram

Single-line diagram (SLD) provide functional information about the electrical design of a system. This type of drawing is also referred to as a one-line drawing. The name of these drawings is derived from the fact that there will be one line between components on the drawing even though there may be more than one conductor used to connect the equipment.

These drawings allow you to become familiar with the electrical distribution system layout and design. It shows how the main components of the electrical system are connected.

You will be able to follow the flow of power through the power distribution system from the incoming power source to each downstream load. A fully developed SLD will include the ratings and sizes of each piece of electrical equipment, circuit conductors, and protective devices.

An example of an SLD is shown in figure 1. This drawing shows a system that has two utility sources connected to a line-up of medium voltage switchgear (MV-1). On this drawing you can follow how power would flow through MV-1 to the lighting panel (LP-1). Single-line diagrams use standard symbols to represent the various components.

For medium voltage equipment with ratings greater than 1,000VAC, equipment will typically be referred to using standard device numbers that are defined by ANSI, and by project-specific symbols or acronyms which are defined on the drawing. In figure 1, the medium voltage circuit breakers are shown as a box with "52", which is the ANSI device number for an AC circuit breaker. A list of common ANSI device numbers can be found in appendix A. The components mounted in the medium voltage switchgear are enclosed by the dashed lines around the equipment symbols. This drawing shows the medium voltage switchgear ratings for voltage (13.8kV), current capacity (1,200 amps) and short circuit rating (25KA).

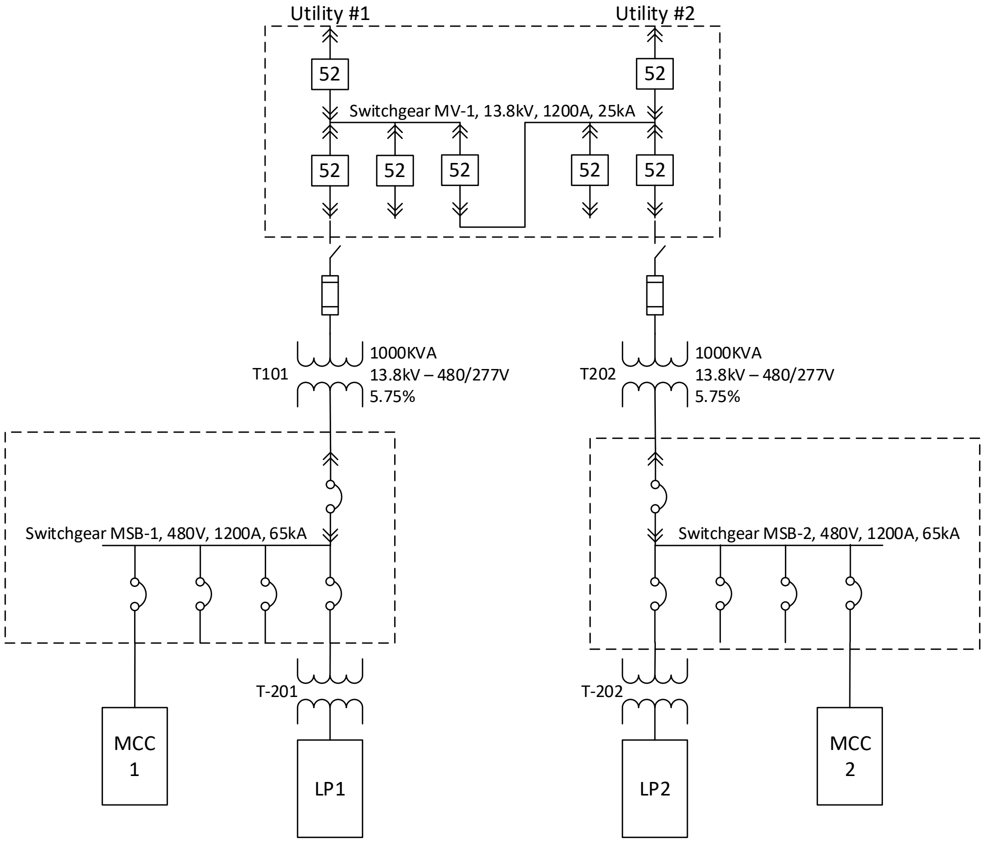

Figure 1: Single-Line Diagram

Figure 2 shows a more detailed SLD of the medium voltage switchgear (MV-1). Medium voltage circuit breakers do not have a protective relay or trip unit built-in that will cause the breaker to open during a fault condition, so there is a protective relay indicated by the circle labeled “PR”. There is also a power meter indicated by the circle labeled “PM”. These are not universal designations, so they should be identified in the notes on the drawing.

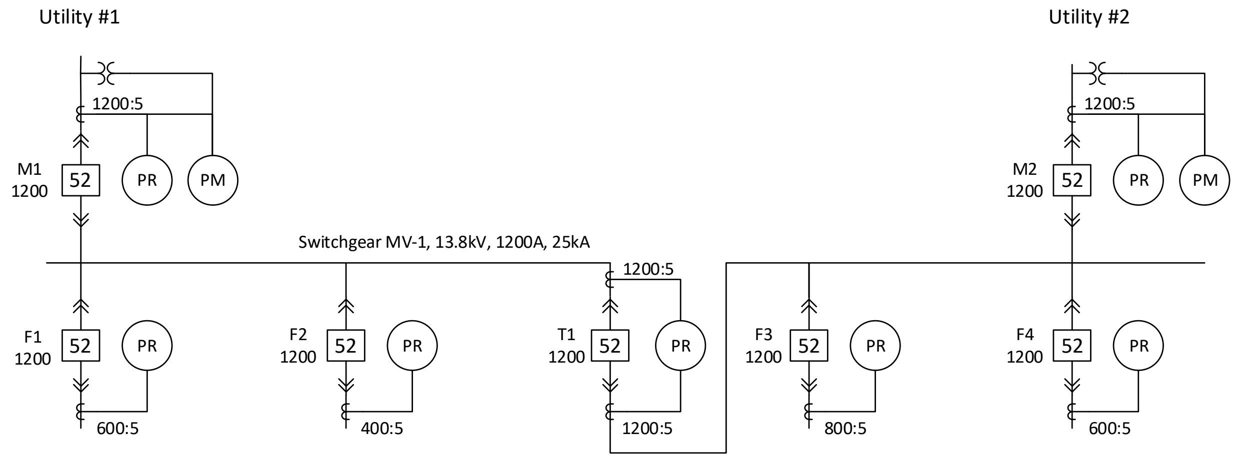

Figure 2: Single-Line Diagram with more details

The protective relay and power meter have inputs from the voltage transformers (VT) and current transformers (CT). The VTs are represented by the symbol in figure 3 and the CTs are represented by the symbol in figure 4.

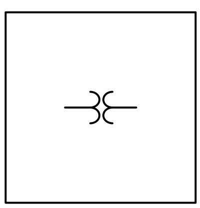
Figure 3: Voltage Transformer (VT) Symbol

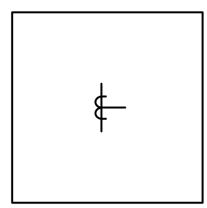
Figure 4: Current Transformer (CT) Symbol

Voltage transformers are used to change the voltage from 13.8KV to 120V which can be connected to the protective relay and power meter. Using a standard ratio between the high and low voltages allows the digital protective relays and power meters to calculate the actual value of the voltage. Current transformers are used to provide a proportional measurement of the current. Using a standard ratio allows the digital protective relays and power meters to calculate the actual value of the current flowing in the system.

The lines around the circuit breaker that look like double arrow heads indicate that these breakers are removeable without unbolting busbar connections. The symbol is shown in figure 5. This is commonly referred to as a drawout, removeable, or withdrawable breaker. Removing the circuit breakers may be assisted by a mechanical lever, ball screw or other mechanical means. These circuit breakers use spring-loaded finger clusters that maintain contact pressure on the switchgear busbar when properly installed.

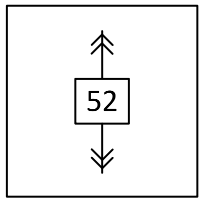

Figure 5: Withdrawable Medium Voltage Circuit Breaker Symbol

In Figure 1, power flows from the utility through the breakers in switchgear MV-1 to transformer T101 which is represented by the symbol in figure 6. The transformer symbol will include rating information as shown in figure 7, such as the primary and secondary voltage, the KVA power rating, and impedance. In this case the primary voltage is 13.8kV and the secondary voltage is 480/277V.

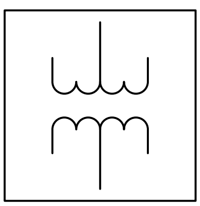

Figure 6: Transformer Symbol

Transformer Ratings
1000 KVA
13.8kV – 480/277V
5.75%

Figure 7: Transformer Rating Information

The secondary side of this transformer is connected to switchboard MSB-1. MSB-1 shows breakers for low voltage (LV) power distribution (<1,000VAC). The main breaker in MSB-1 is shown as a drawout breaker indicated by the double arrowhead on both sides of the breaker and shown in figure 8. Since the feeder breakers do not have the double arrowhead, they are not drawout construction, and are referred to as fixed-mounted circuit breakers as shown in figure 9.

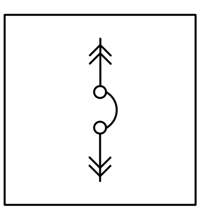

Figure 8: Drawout LV Circuit Breaker

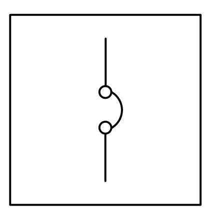

Figure 9: Fixed-Mounted LV Circuit Breaker

Feeder breakers in MSB-1 are shown providing power to a motor control center (MCC-1) and a transformer (T-201) and lighting panel (LP-1). MCC-1 and LP-1 are shown as simple boxes on this drawing to reduce the complexity of the drawing. The details for the MCC will typically be shown as an SLD on another drawing. Lighting panels are typically shown on a panelboard schedule on other drawing sheets.

An example of an SLD for a motor control center is shown in figure 10. This shows that the input power is connected to a main circuit breaker, rated 600A.

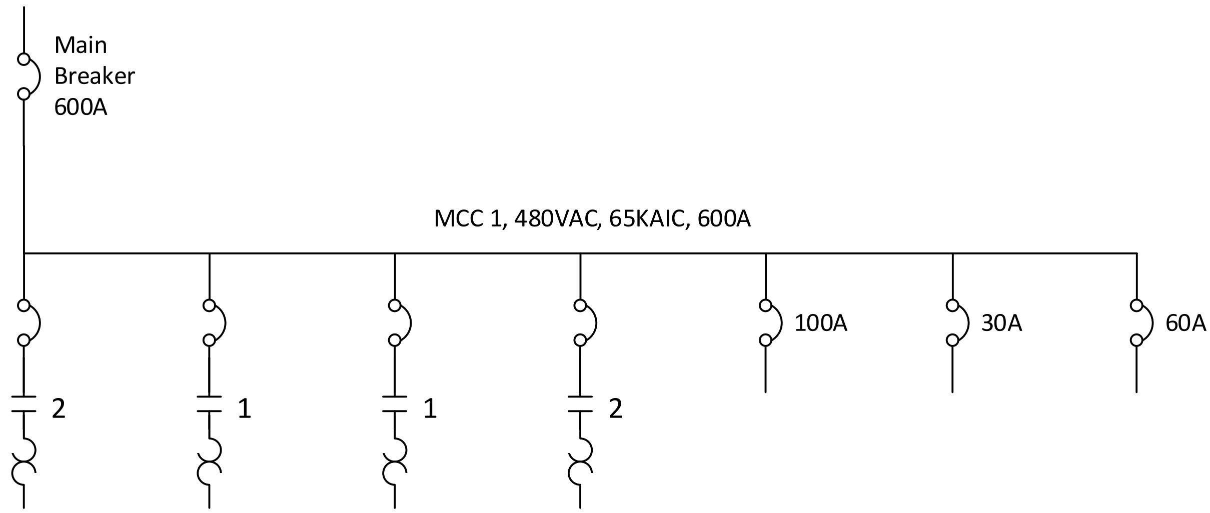

Figure 10: Low Voltage MCC Single Line Drawing

The figure shows four motor starters on the left, which use a combination of a circuit breaker, contactor, and overload. It also shows 3 circuit breakers on the right side. The contactor and overload are shown using the symbols in figures 11 and 12.

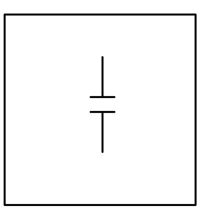

Figure 11: Contactor Symbol

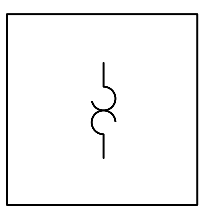

Figure 12: Overload Symbol

Three-Line Drawings

A three-line drawing provides more detail than a single-line drawing. Where the SLD shows one line between devices, the three-line drawing shows all three conductors. This type of diagram will typically show more detail for the control devices as well. Figure 13 is an example of a three-line drawing of switchgear with a main breaker and two feeder breakers. This drawing shows that there are three CTs associated with each circuit breaker and there is a common set of VTs which are wired to the protective relay (PR) for each circuit breaker.

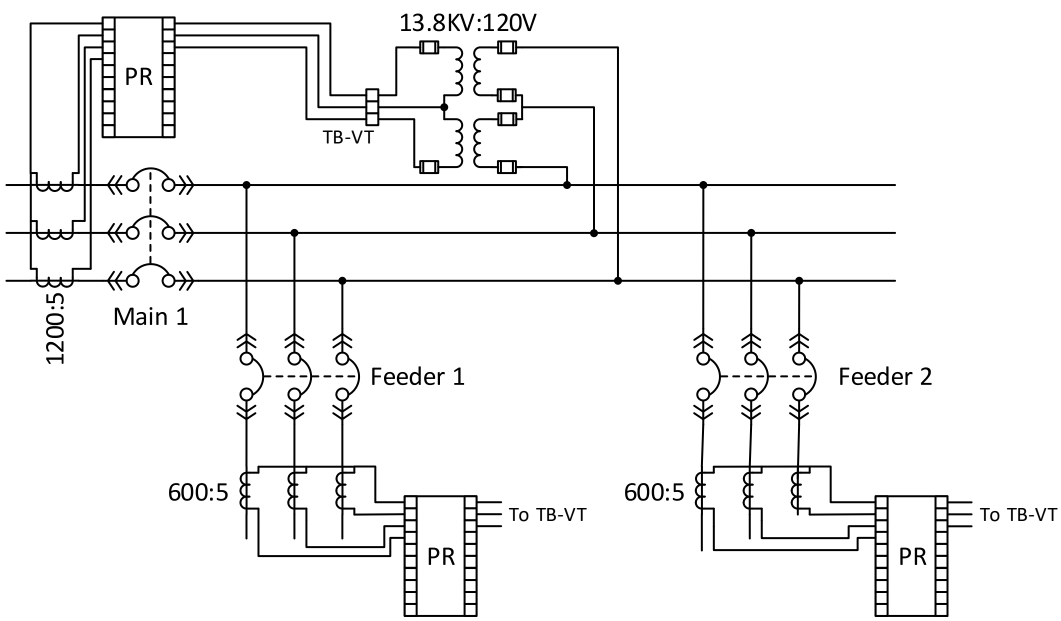

Figure 13: Three-Line Drawing example

Riser Diagram

A riser diagram is a drawing that pictographically shows the physical layout of a building's major power distribution components. The emphasis for a riser diagram is identification of the equipment and its location in the building. This is commonly used in multi-story buildings. The major items of electrical equipment will be identified floor by floor, along with the location on each floor. Figure 14 shows an example of a 4-story building.

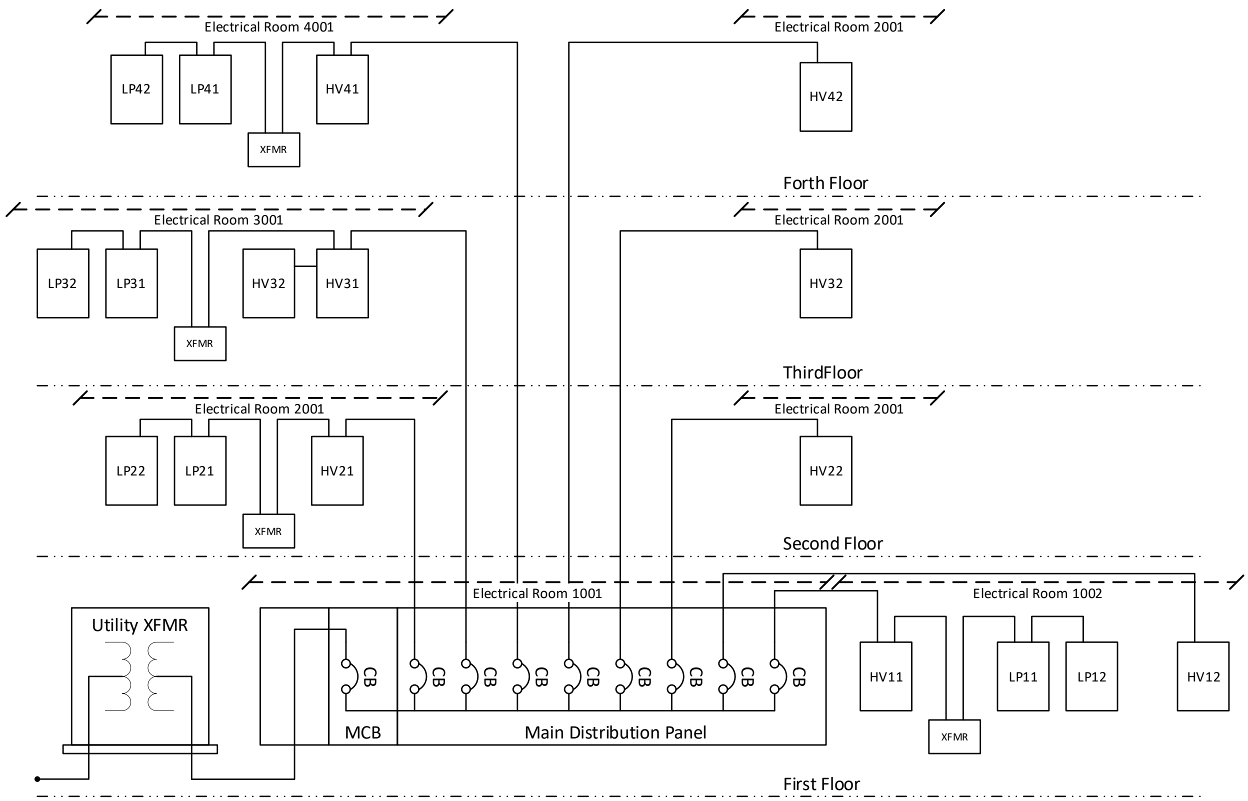

Figure 14: Riser diagram of a 4-story building

Schematics and Wiring Diagrams

Schematic drawings also provide functional information about the electrical system or components; however, they provide more details compared to a single-line diagram. While the SLD focuses on the power connections, schematics include connections between power and control devices such as relays, fuses, switches, lights, and instruments. The main purpose of a schematic diagram is to emphasize control circuit elements and how their functions relate to each other. Schematics are a valuable troubleshooting tool because they can be used to identify how components are connected to one another. Schematics are drawn for the ease of understanding functionality and how components are connected, rather than trying to show the actual physical location of the components.

Wiring diagrams are similar to schematics by providing functional information about the connection of power and control devices. However, wiring diagrams place a higher emphasis on the physical layout of the equipment and their interconnections.

Figure 15 shows a schematic for a motor starter in a motor control center. This shows more detail in the power circuit by showing the three wires that are used to connect power to the circuit breaker, contactor, overload, and motor.

With its emphasis on functionality, the control circuit is shown as a ladder diagram. The control voltage is from X1 to X2 and is distributed down the vertical lines on the right and left side. The control to start the motor is shown in the horizontal rung through the STOP push button, START push button, "M" contactor, and the overload (OL). A schematic using this type of ladder diagram makes it easy to see which control devices are in series to produce a specific output.

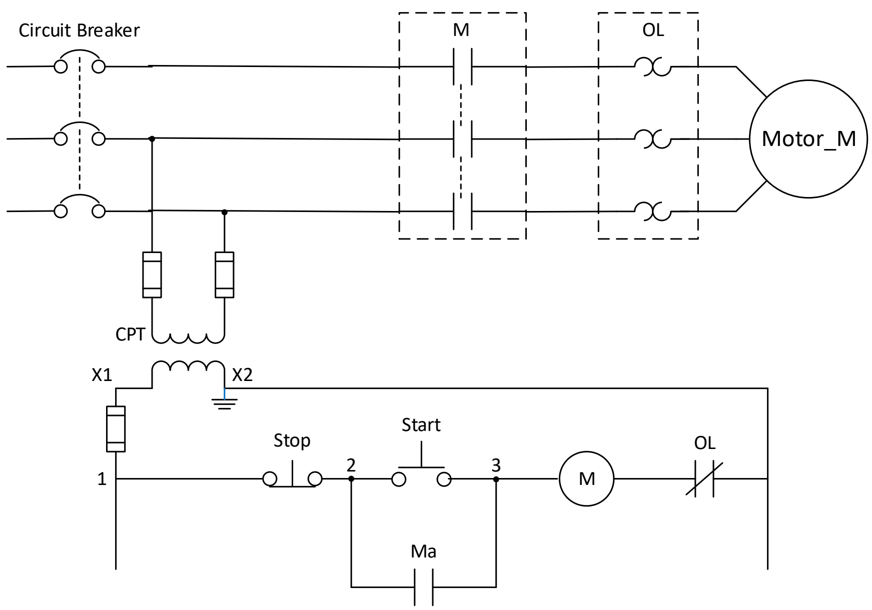

Figure 15: Motor starter control schematic

A wiring diagram for this circuit is shown in figure 16. In this case the power circuit has been turned vertically, but it is identical to the way the power circuit is shown in the schematic. The major difference is in the control circuit. With a higher emphasis on the physical device locations, the devices and terminals associated with the contactor (M), the overload (OL), and the push button station with the START and STOP buttons are grouped together and shown in a dashed box.

In this case, the box for the contactor shows the three contacts in the power circuit, the contactor coil (M), and the auxiliary contact (Ma). This makes it clear what wires should be attached to the contactor when someone goes to look at it in the field.

The box for the overload shows the three overloads in the power circuit and the auxiliary contact.

This diagram makes it clear what wires are connected between each device. It is not as easy to follow the circuit through the STOP button, the START button, the contactor coil (M), and the overload (OL) when compared to the schematic. Schematics and wiring diagrams are both useful depending on your needs.

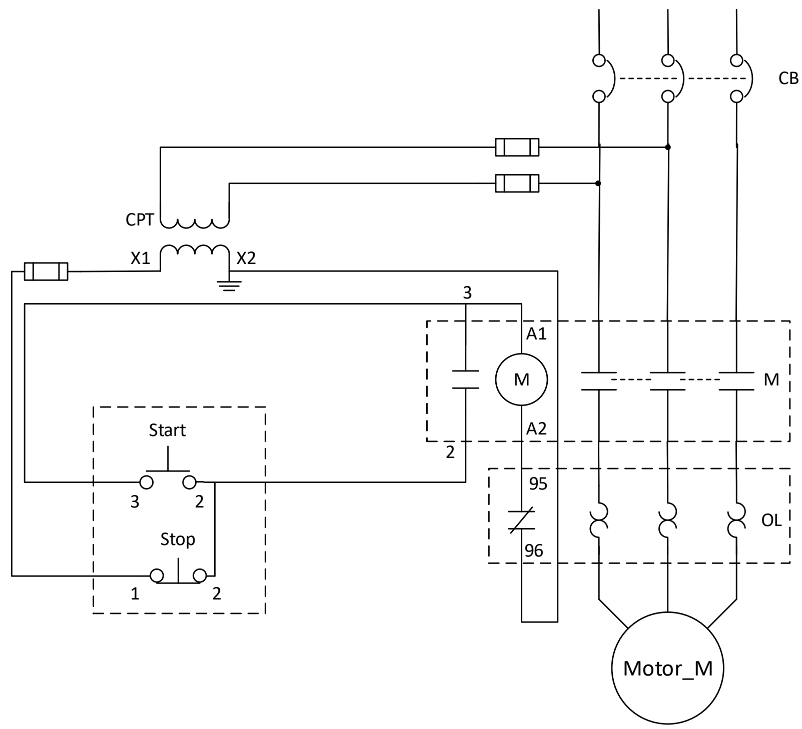

Figure 16: Motor starter wiring diagram

Schedules

Electrical distribution schedules are used to provide tabular information. Tabular information is similar between projects; however, you will find variations in how the information is presented.

A cable and conduit schedule is a table of information about the conduit and cable used between equipment in an installation. Typical information shown on this schedule will be the devices at each end, length, type of conductor, and size. An example of a cable and conduit schedule is shown in Figure 17. The information in this schedule is useful for estimating project costs for original installation or replacement, identifying the end points of the cables, and for use in power system studies.

Power Circuits - Cable and Conduit Schedule								
Load Name	Circuit Number	Voltage	Conductor Size	Number of Sets	Conduit Size	Length (ft)	From	To
T101	MV101	13.8kV	3 - #2	1	5"	100	MV-1	T101
T202	MV202	13.8kV	3 - #2	1	5"	175	MV-1	T202
MSB-1	MSB1	480V	3 - 400kcmil	5	3"	75	T101	MSB-1
MSB-2	MSB2	480V	3 - 400kcmil	5	3"	200	T202	MSB-2
MCC-1	FDR1-1	480V	3 - 350kcmil	2	3"	50	MSB-1	MCC-1
T-201	FDR1-4	480V	3 - #1	1	1 1/4"	100	MSB-1	T-201
T-202	FDR2-1	480V	3 - #1	1	1 1/4"	120	MSB-2	T-202
MCC-2	FDR2-4	480V	3 - 350kcmil	2	3"	150	MSB-2	MCC-2
LP1	LP1	480V	3 - 250kcmil	1	2 1/2"	25	T-201	LP1
LP2	LP2	480V	3 - 250kcmil	1	2 1/2"	25	T-202	LP2

Figure 17: Cable and conduit schedule

Panelboard and switchboard schedules provide more detail about these types of equipment than is typically shown on a single-line diagram. Information that can be found on a panelboard schedule includes circuit numbers, circuit names, load name, circuit breaker ratings, and load current. An example of a panelboard schedule is shown in Figure 18.

PANELBOARD F2-101 SCHEDULE														
400	Bus Amps		400/277		Volts			35		KAIC		☑		Surface Mount
3	Phase		4		Wire							☐		Flush Mount
	Load Amps			BKR	WIRE	CKT	PHASE	CKT	WIRE	BKR	Load Amps			
Circuit Description	A	B	C	TRIP	SIZE	No.	A-B-C	No.	SIZE	TRIP	A	B	C	Circuit Description
HVAC-1	27			35	8	1		2	8	35	27			HVAC-2
		27				3		4				27		
			27			5		6					27	
PUMP-1	40			60	8	7		8	8	60	40			PUMP-2
		40				9		10				40		
			40			11		12					40	
LIGHTING BLDG 1	10.9			20	10	13		14	2/0	175	124			MCC-1
LIGHTING BLDG 2		11.7		20	10	15		16				124		
LIGHTING BLDG 3			12.1	20	10	17		18					124	
SPARE				20		19		20		20				SPARE
SPARE				20		21		22		20				SPARE
SPARE				20		23		24		20				SPARE
Sub Total Amps	77.9	78.7	79.1								191	191	191	Sub Total Amps
Total Amps	268.9	269.7	270.1											

Figure 18: Panelboard schedule

Electrical Power System Studies

The term “power system study” is often used as a general term to include a range of studies. This section of the course provides information about the most common types of power system studies, a description of the studies, and the reasons for performing the studies.

Short Circuit Study

Before we discuss the short circuit study it is important to understand what a short circuit is and how it impacts the power system, equipment, and people. A short circuit occurs when conductors from two different phases come in contact with each other. When this happens, the current will rapidly rise to thousands of amps. The high current produces high mechanical stresses and excessive heat which has the potential to create a fire or explosion which may damage equipment and cause injury or death.

The purpose of a short circuit study is to determine the highest amount of current that will flow through the power distribution system under a short circuit fault condition. This is commonly referred to as the “available fault current”.

All equipment in an electrical power distribution system will have a short circuit rating. The short circuit rating is the fault current that the equipment can experience without sustaining damage exceeding defined acceptable criteria. These ratings apply to service entrance equipment, switchgear, breakers, panel boards and electrical control cabinets. The results of a short circuit study can be used to verify that the equipment used in the power system has a short circuit rating that is higher than the available fault current.

If the short circuit ratings of equipment are below the available short circuit current, the equipment may fail to interrupt the fault current in a safe manner. Under this condition, there is the potential for equipment damage and personnel injury or death when a short circuit occurs. If this situation is identified, corrective action should be taken to reduce the amount of available short circuit current or increase the equipment short circuit ratings.

A detailed short circuit study can be performed using a variety of software tools that are available. Information required for the short circuit study include:

1. The utility available short circuit current
2. Service entrance transformer size, voltage rating, and impedance
3. Other sources of power generation (solar, battery systems, generators)
4. Large motor loads
5. Cable sizes and lengths between power distribution equipment
6. Single-line diagram of the system

When a project is in the design stage, a short circuit study can be performed by making assumptions about some of the data listed above. Initial calculations can be made using the service entrance transformer size, assuming a typical impedance and unlimited utility available short circuit current. This will provide a rough order of magnitude for the available short circuit current. As the project continues through the design stages, the calculations can be refined as more detailed information is available. When a design is completed, a final short circuit study should be completed using the final detail information.

A short circuit study should be performed during new construction, when replacing equipment and when significant changes are made to the system. Most of the information required for a short circuit study will be contained on a well-maintained single-line diagram. For this reason, SLDs for a site should be kept up to date as changes are made at the facility.

Coordination Study

A coordination study is an analysis of the protection settings of devices in an electrical power system. The objectives are to confirm that the protection settings will protect equipment from excessive damage, determine the clearing time under fault conditions, and provide selectivity between upstream and downstream protective devices. The fault conditions to be analyzed are short circuit, overloads, and ground fault.

Selectivity in electrical system protection is the concept of minimizing the impact on the system during a fault condition. This is accomplished by shutting down the smallest part of the system possible. The desired response is for the protective device that is closest to the fault to operate, shutting down power to the smallest portion of the system.

The coordination study uses the characteristic protection curve for the devices plotted on a log-log graph to show areas of concern as well as tabular data. An example of the graphical plot of the coordination data is shown in Figure 19.

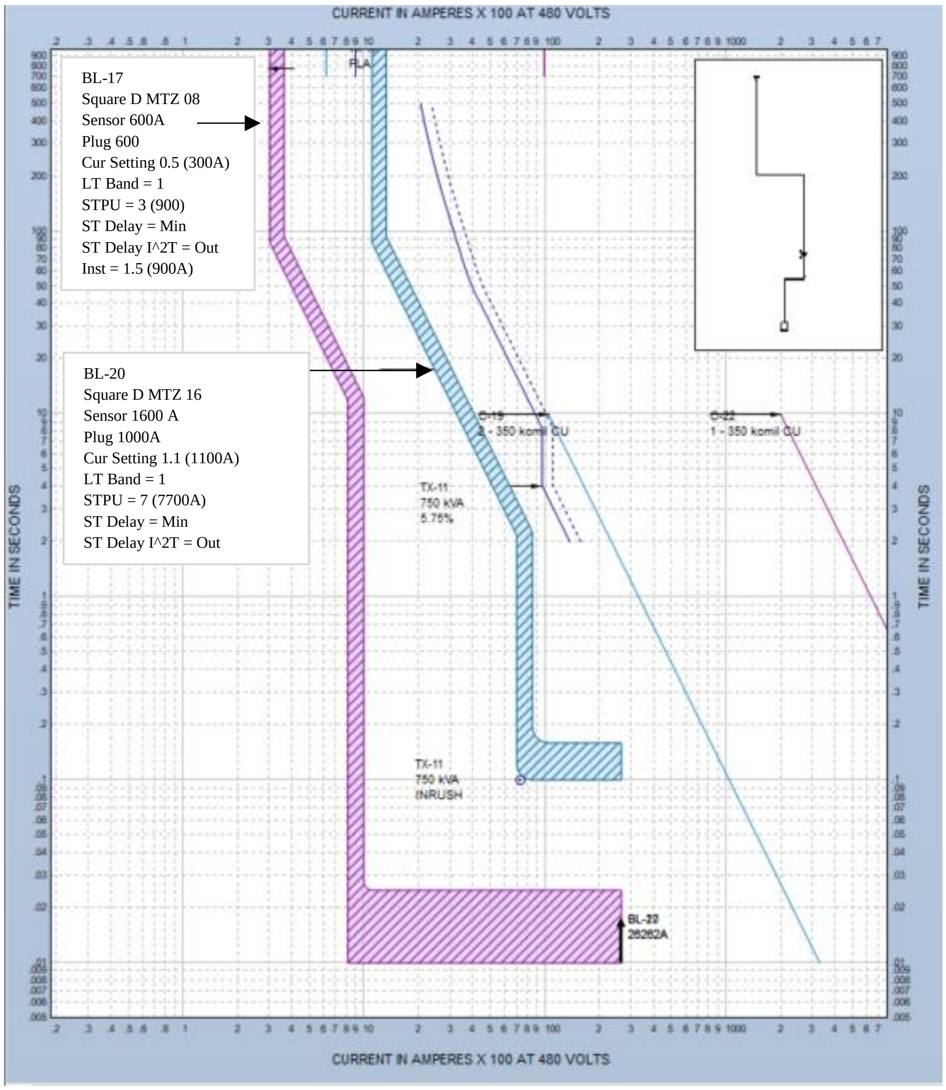

Figure 19: Coordination study graph

The tabular data produced by the coordination study will provide an engineer with the settings that should be used to setup the circuit breaker trip unit during commissioning of the system during installation, or when changes are made to the system. Some of the settings may be included on the graph as shown near the left edge of figure 19.

Arc Flash Study

An arc flash study calculates the arc flash incident energy at specific points in the electrical distribution system when an arc-fault occurs. An arc-fault is a fault condition where an arc occurs between two conductors resulting in an explosion. The incident energy is the amount of energy that could be released if an arc flash were to occur.

This study also provides the arc flash boundary. This boundary is the distance from equipment where a person will be exposed to incident energy of 1.2 cal/cm^2 during an arc flash event. At this distance, a person without appropriate PPE would receive second-degree burns.

An arc flash study should be performed as a part of an arc flash / electrical safety program. An arc flash safety program should include the arc flash study, arc flash and shock hazard labels applied to electrical equipment, and electrical safety training for all people who will be around electrical equipment.

The level of incident energy should be used along with the guidelines in NFPA 70E for the recommended personal protective equipment (PPE) that should be worn by people who will be within the arc flash boundary.

Information required to perform an arc flash study includes:

1. Electrical system single-line diagram
2. Field verification of the information on the SLD and data from protective devices, equipment ratings and cable lengths
3. A short circuit study of the existing system

After the short circuit study is completed, there is an iterative process of reviewing the selectivity of the short circuit study and performing the arc flash calculations. The reason for this iterative process is that if you introduce time delays in the protective settings to provide better selectivity, this time delay will increase the time that an arc flash will last, which increases the incident energy and danger to personnel within the arc flash boundary. During this review of the selectivity and arc flash incident energy, the engineers should review options to reduce the amount of arc flash incident energy while maintaining protective coordination and selectivity.

NFPA 70E – Standard for Electrical Safety in the Workplace, section 130.5 requires that an arc flash assessment shall be reviewed at intervals not to exceed 5 years. This is just one part of an overall electrical safety program as part of an employer's occupational health and safety program.

Load Flow

A load flow study, sometimes called a power flow study is an analysis of the flow of electrical power in an electrical system. The objective of the load flow study is to calculate the flow of power and current, under different load conditions and the effect on voltage. This should include the flow of real power and reactive power under steady-state conditions.

Load flow studies can be used for system planning. This study is especially valuable on larger systems with multiple sources of power. The multiple sources may be multiple utility sources or on-site energy resources such as photovoltaic solar power, battery energy storage systems or generators powered by diesel or natural gas. The load flow study will show how power will flow from the various sources and confirm whether there is adequate power for the connected loads.

A load flow study can be created under different scenarios to provide the design team with greater insight into the system resilience and availability of the electrical system during abnormal conditions. An example would be to run a scenario where only one of the two utility feeders is available and determine whether the single utility feeder plus the on-site generation is sufficient to power the loads. If there is not adequate power, then analysis can be made to determine how to compensate for this situation. The solution could be an increase in on-site generation or a decision to turn off non-essential loads until the operating load is below the level of available power. Considering the possible solutions and their cost will allow a financial analysis to be made for the additional investment versus the financial and other costs of equipment being unavailable.

The load flow study will also provide information about the magnitude and phase-angle of the voltage at different points on the single-line diagram. As electrical current flows through equipment and cables, there is a drop in the voltage level. The study will identify whether there are voltage drops in the system that are unacceptable, allowing for engineers to make changes to the design to compensate for this condition. Changes could include transformer ratio or tap changes, the addition of capacitors or harmonic compensation devices.

Bringing it All Together

All engineering disciplines have unique terminology and methods for communicating information. This course has shown several types of drawings for communicating information about an electrical power system.

1. Single-line drawings
2. Three-line drawings
3. Riser diagrams
4. Schematics
5. Wiring Diagrams
6. Schedules

Some of the most common symbols used in electrical power system drawings were presented.

Several electrical engineering studies were presented that provide information to: verify proper equipment ratings to be used during commissioning and setup; confirm hazards that should be protected against; and confirm system resilience and how it will perform during abnormal conditions.

1. Short circuit study
2. Coordination study
3. Arc flash study
4. Load flow study

This information provides a foundation to understand electrical power distribution systems, the types of information that can be found on electrical drawings, and studies that are used to confirm proper equipment applications for safe operation and precautions that should be taken for personnel protection.

Appendix A – ANSI Device Numbers

1 - Master Element
2 - Time Delay Starting or Closing Relay
3 - Checking or Interlocking Relay
4 - Master Contactor
5 - Stopping Device
6 - Starting Circuit Breaker
7 - Rate of Change Relay
8 - Control Power Disconnecting Device
9 - Reversing Device
10 - Unit Sequence Switch
11 - Multifunction Device
12 - Overspeed Device
13 - Synchronous-speed Device
14 - Under speed Device
15 - Speed - or Frequency-Matching Device
20 - Electrically Operated Valve
21 - Distance Relay
23 - Temperature Control Device
24 - Volts per Hertz Relay
25 - Synchronizing or Synchronism-Check
26 - Apparatus Thermal Device
27 - Undervoltage Relay
29 - Isolating Contactor
30 - Annunciator Relay
32 - Directional Power Relay
36 - Polarity or Polarizing Voltage Devices
37 - Undercurrent or Underpower Relay
38 - Bearing Protective Device
39 - Mechanical Conduction Monitor
40 - Loss of Field Relay
41 - Field Circuit Breaker
42 - Running Circuit Breaker
43 - Manual Transfer or Selector Device
46 - Reverse-phase or Phase-Balance Relay
47 - Phase-Sequence Voltage Relay
48 - Incomplete-Sequence Relay
49 - Machine or Transformer Thermal Relay
50 - Instantaneous Overcurrent
51 - AC Time Overcurrent Relay
52 - AC Circuit Breaker
53 - Exciter or DC Generator Relay
54 - High-Speed DC Circuit Breaker
55 - Power Factor Relay
56 - Field Application Relay
59 - Overvoltage Relay
60 - Voltage or Current Balance Relay
62 - Time-Delay Stopping or Opening Relay
63 - Pressure Switch
64 - Ground Detector Relay
65 - Governor
66 - Notching or jogging device
67 - AC Directional Overcurrent Relay
68 - Blocking or "out of step" Relay
69 - Permissive Control Device
71 - Level Switch
72 - DC Circuit Breaker
74 - Alarm Relay
75 - Position Changing Mechanism
76 - DC Overcurrent Relay
78 - Phase-Angle Measuring or Out-of-Step
79 - AC-Reclosing Relay
81 - Frequency Relay
81O - Over Frequency
81R - Rate-of-Change Frequency
81U - Under Frequency
83 - Automatic Selective Control of Transfer
84 - Operating Mechanism
85 - Carrier or Pilot-Wire Receiver Relay
86 - Lockout Relay
87 - Differential Protective Relay
87B - Bus Differential
87G - Generator Differential
87T - Transformer Differential
89 - Line Switch
90 - Regulating Device
91 - Voltage Directional Relay
92 - Voltage and Power Directional Relay
94 - Tripping or Trip-Free Relay

